WAR DEPARTMENT

CORPS OF ENGINEERS, U. S. ARMY

EXPERIMENTS TO DETERMINE THE BACK-WATER EFFECTS OF SUBMERGED SILLS IN THE ST. CLAIR RIVER

PAPER 16

OF THE

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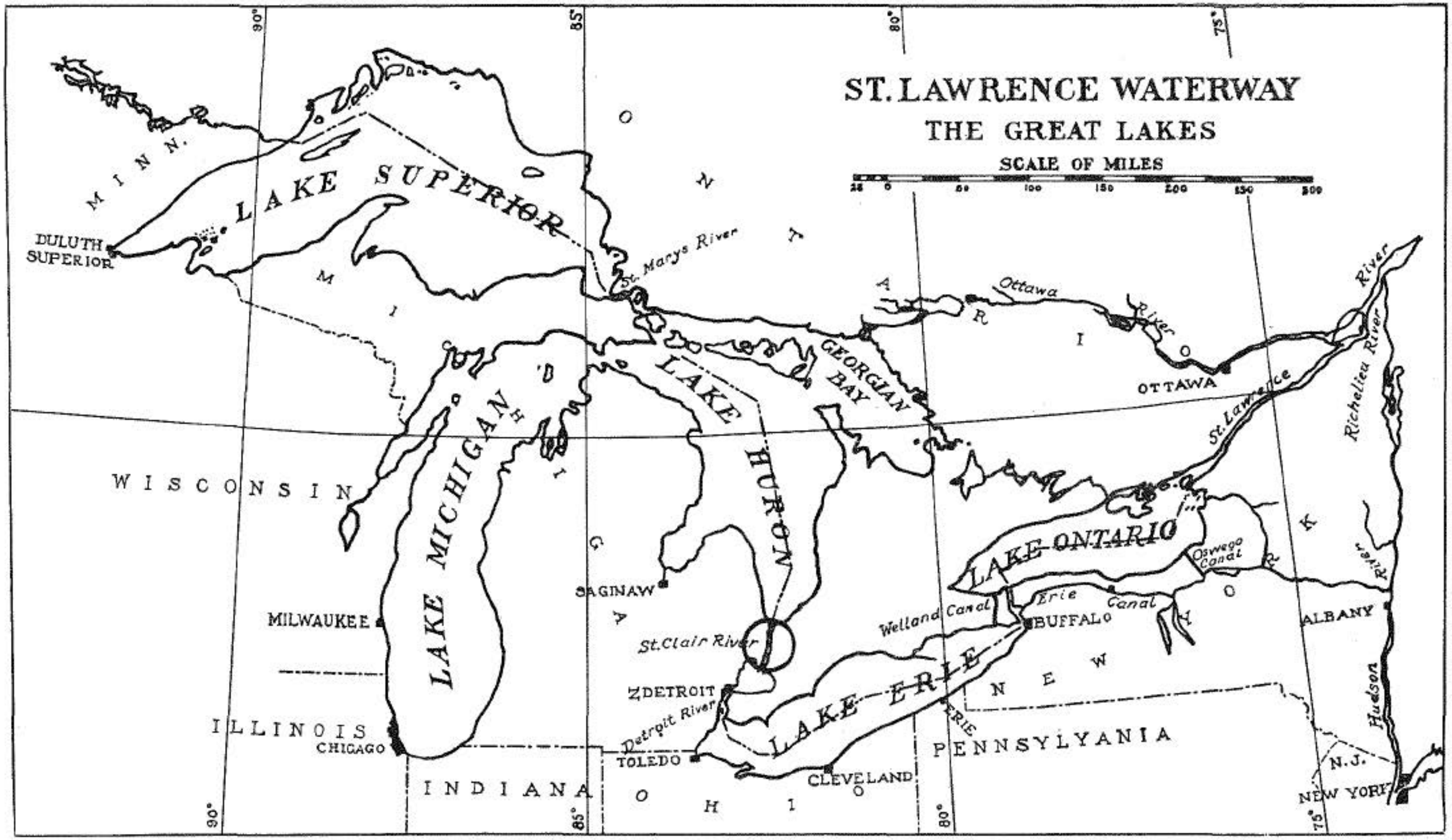
ST. LAWRENCE WATERWAY
THE GREAT LAKES
SCALE OF MILES
LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
GEORGIAN BAY
LAKE ONTARIO
LAKE ERIE
MINN.
WISCONSIN
ILLINOIS
INDIANA
OHIO
MICHIGAN
ONTARIO
NEW YORK
PENNSYLVANIA
N.J.
DULUTH
SUPERIOR
MILWAUKEE
CHICAGO
SAGINAW
DETROIT
TOLEDO
CLEVELAND
ERIE
BUFFALO
OTTAWA
ALBANY
NEW YORK
St. Marys River
St. Clair River
Detroit River
Welland Canal
Erie Canal
Oswego Canal
Ottawa River
St. Lawrence River
Richelieu River
Hudson River
90°
85°
80°
75°

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EXPERIMENTS TO DETERMINE THE BACKWATER EFFECTS OF SUBMERGED SILLS IN THE ST. CLAIR RIVER

Synopsis

1. This report describes the experiments made at the U. S. Waterways Experiment Station to determine the effects of proposed sills in the St. Clair River, and discusses the information obtained from the experiments. The tests indicate that:

(a) It is possible to secure the desired rise in level of Lake Huron by the use of sills at the locations proposed.

(b) It is necessary to use sills of different cross-section from that proposed in order to obtain the desired effects.

(c) Alternative locations for sills in the same reach of the river may be used.

(d) Within reasonable limits, the backwater produced by any individual sill is not reduced by the proximity of another sill.

(e) The backwater effects of the sills increase as the discharge of the river is increased.

(f) The large eddy on the Canadian side of the river, opposite the Park street gage in Port Huron, is very much reduced in extent by the sills.

Introduction

2. The Great Lakes constitute a great natural waterway along a part of the northern boundary of the United States, and an enormous amount of iron ore, coal, wheat, and other commodities is transported on them. Many more tons of freight are carried each year through the St. Clair and Detroit Rivers, which connect Lake Huron and Lake Erie, than are carried through both the Panama and Suez canals, despite the fact that navigation on the Great Lakes is closed by ice for about five months of every twelve.

3. To a considerable extent, the economic welfare of this country and of Canada depends on the uninterrupted flow of this traffic. Consequently, the efficient maintenance and improvement of the waterway is of prime public interest. The lakes themselves offer no obstructions to navigation, but the channels connecting them have required improvements, and many harbors have had to be enlarged and deepened before they could satisfactorily fulfill the requirements of shipping.

4. One of the principal factors limiting present navigation on the Great Lakes is the depth of harbors. Freighters are loaded until they can just enter the harbors and reach their unloading docks. Whenever the slowly fluctuating lake-levels rise, the ships are loaded to take advantage of the increased available depth. An extra one-half foot of usable draft would permit the load of a large freighter to be increased by several hundred tons, and the transportation by each vessel of many thousands of tons more of freight in a season.

5. For some years past, there has been a slight but perceptible lowering of the levels of Lakes Michigan and Huron, due to diversion of water from the Great Lakes and to dredging in the channels connecting the lakes. Numerous plans have been advanced to restore the lakes to the levels at which they stood before they were artificially lowered, and so to increase the capacity of the waterway. Most of these plans involve regulating and compensating works at the lake outlets, similar to those already installed at the outlet from Lake Superior.

6. One of the most promising schemes for restoring the level of Lake Huron contemplates the construction of a number of submerged sills in the St. Clair River, the outlet of the lake. The tops of the sills would be low enough for vessels to pass over them without interference. The effect of such sills would be to decrease the discharge capacity of the river for any given stage of the lake, due to the decreased cross-section and increased roughness of the river channel. Therefore, in order for the river to discharge the same amount of water, the lake level would have to stand higher after the sills were constructed.

7. There was no question but that such sills would operate to raise the levels of Lakes Huron and Michigan. However, when it came to the question of the amount of rise which would be produced, it was found that there was no existing information upon which to base any definite prediction. In the absence of such information it was necessary to turn to experiments on hydraulic models.

8. Model tests of a preliminary nature, made by the U. S. Lake Survey at the hydraulic laboratory of the University of Michigan, served to indicate to some extent the comparative effects of different types of sills and to indicate that further tests should be made. With the facilities available there, however, it was not considered practicable to make a complete and satisfactory study, and the problem was referred to the U. S. Waterways Experiment Station.

Authority

9. Authority for this study was contained in the 2nd Indorsement, dated October 18, 1932, by the Chief of Engineers, to a letter dated October 7, 1932, from the President, Mississippi River Commission, in which the proposed program of experiments was submitted for approval.

Purpose of the Experiments

10. It has been computed by the U. S. Lake Survey Office at Detroit that an increased stage of 0.54 foot is necessary to restore Lakes Michigan and Huron to the levels of 1889-1899. The plan for regulating or compensating works proposed by the St. Lawrence Board and approved by Congress requires the construction of submerged sills, at the head of the St. Clair River, whose crests shall be not less than 30 feet below standard low water, and which shall not reduce the cross-sectional area of the channel at standard low water to less than 40,000 square feet. The Lake Survey Office has submitted a tentative plan for the location of eight sills (see Plate 3) which, by computations based on assumptions made by the St.

Lawrence Board, would produce an increased stage, or backwater effect, of 0.53 foot. The purpose of these tests was to determine experimentally the effect of these proposed sills, and further to determine the best combination of number, type, and location of sills necessary to produce the desired backwater of 0.54 foot. It was also desired to determine the effects of the sills on the distribution of velocities in the river channel, and to secure any other pertinent data that might be indicated by the models.

Outline of Procedure

11. The experiments that were undertaken in the course of this investigation can be divided into four different series, as follows:

(a) Tests made in the standard steel flume to determine the comparative backwater effects of sills of different cross-sections. These tests were planned to check and extend the data obtained at the University of Michigan. A steel flume 3½ feet wide was used, in which model sills were built to 1/16 natural size. Depths of water in the flume were maintained at 1/16 and velocities at 1/4 of those in the river, in accordance with the laws of similitude.

(b) Tests on an outdoor model of the St. Clair River, built to a vertical scale of 1:30 and a horizontal scale of 1:100. Different types of sills, in various combinations, were placed in this model, and the backwater effects were measured. The results were taken as indications of the comparative backwater effects that would be produced by the different types of sills when placed in the river, but, due to the circumstances encountered, they were not accepted as indications of the absolute backwater effects.

(c) Tests on an outdoor model similar to that noted in (b), for which both the vertical and horizontal scales were 1:100, so that the effects of scale distortion were eliminated. In this case it was possible to operate the model in more strict accordance with the laws of similitude, and the results were considered as giving quantitative indications of the performance of the prototypes.

(d) Tests made in a tilting flume, 2.4 feet wide, to determine the backwater effects of various types and numbers of sills. The sills were constructed to a scale of 1:100, and velocities of about 1/10 those in the river were used. These tests served to indicate the manner in which the backwater effect varied with different velocities and with different spacing of sills.

12. It is desirable to define the term "backwater effect," so often used in this report. The backwater effect of any sill or set of sills in a model (or flume) was found by comparing runs made with and without the sills. When there were no sills in the model (or flume) the difference in water-surface elevation between a point above and a point below the reach where the sills were to be located represented the normal frictional loss between the two points. When the sills were in place, the difference in elevation between the two points represented the normal frictional loss plus the extra loss caused

by the sills. Subtracting this first difference in elevation from the second, then, gave the loss, or the backwater effect, of the sills tested.

Flume Tests

13. As stated in Paragraph 11 (a), flume tests were made to check and extend the data obtained at the University of Michigan. In the Michigan tests (see Appendix E), water at various depths and velocities was run over the model sills, with the intent of securing information covering a considerable range of conditions, so that a general formula could be developed to express the backwater effect in terms of the other actors. However, no formula was devised that would be useful in expressing these results, and there did not appear to be much promise of success in that direction.

14. Consequently, it was decided that the tests at the U. S. Waterways Experiment Station should be made, so far as practicable, only of the particular conditions that exist in the St. Clair River. The model sills tested in the flume are shown on Plate 1. All these sills were constructed of planed lumber and were oiled to minimize warping and swelling. The sills of the "12" series were made to simulate natural sills 12 feet high. This is the maximum height allowable, where the river channel is 42 feet deep, to leave a depth over the sills of 30 feet, in conformity with the requirements of navigation as set forth by the Lake Survey Office. The "7" series represented 7-foot sills, suitable for use where the river channel is 37 feet deep.

Test Set-up:

15. The set-up used in running these tests is shown on Plate 1. Water from the laboratory reservoir was admitted at the upper end of the flume, and passed successively through the baffles, over the model sill, and over an adjustable tailgate, after which it was measured by a 4-foot sharp-crested suppressed weir. Water-surface elevations were measured at the five points indicated on Plate 1. Piezometer openings in the sides of the flume, 10 inches above the bottom, were connected to a row of small buckets set under a slide-rod, on which a single hook gage was mounted in such a manner that it could be used to measure the water level in each of the buckets. Point gages were mounted over the center of the flume at points opposite the upper, center and lower piezometers, to make possible a check on the hook-gage readings. The model sills were always placed so that the lower end of the horizontal crest was opposite the center, or intermediate, piezometer opening, at Station 0.

Procedure:

16. After the measuring weir had been calibrated, hook gages and point gages zeroed, and preliminary runs made to familiarize the operators with the apparatus, regular tests were begun. The velocity and depth of water in the open flume were adjusted to the required values by varying the quantity of flow and by adjusting the elevation of the tailgate. After water levels had reached equilibrium, the elevations of the ends of the tailgate were measured with a level, and ten sets of readings were taken, as rapidly as possible,

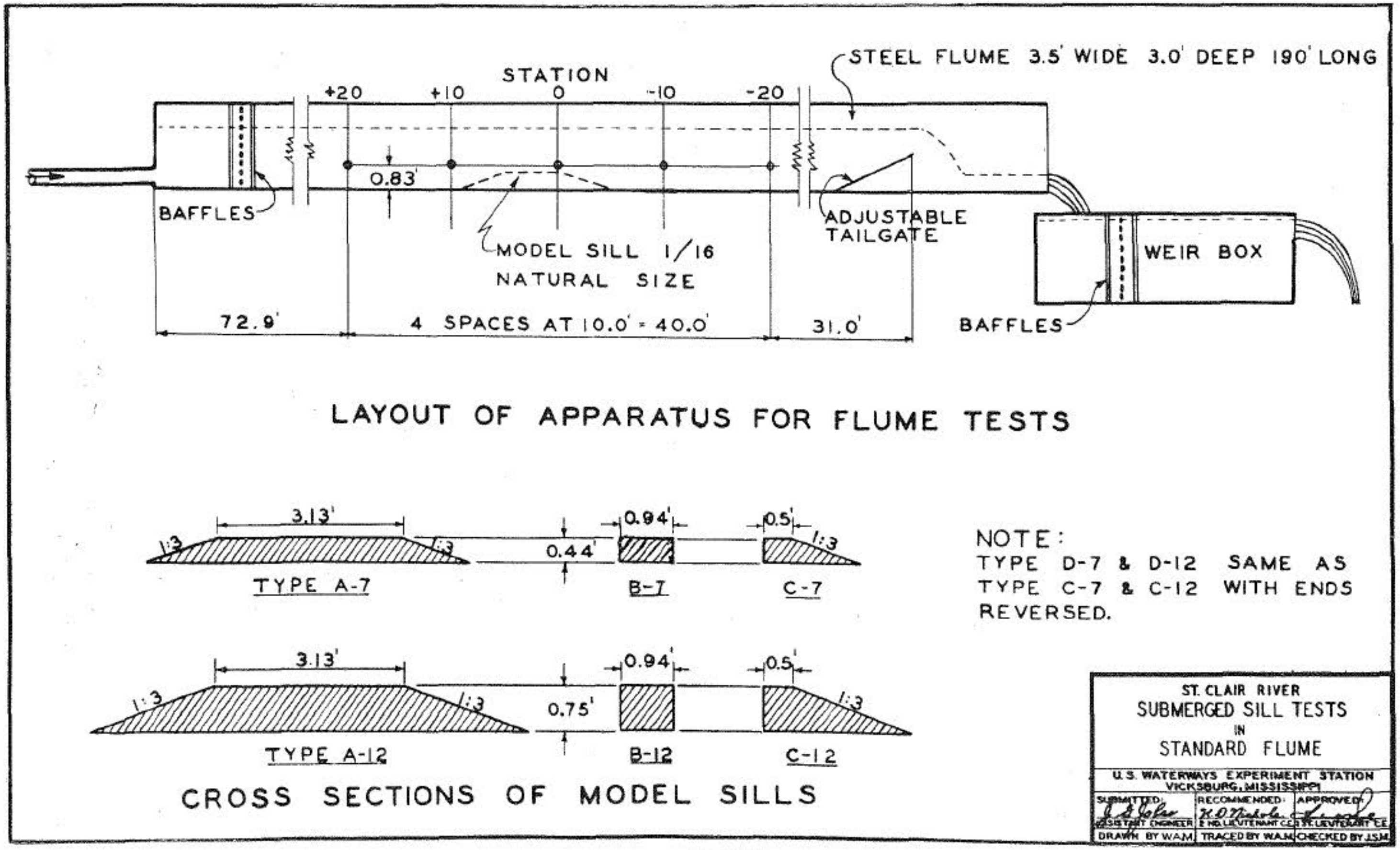
STEEL FLUME 3.5' WIDE 3.0' DEEP 190' LONG
STATION
+20
+10
0
-10
-20
0.83'
BAFFLES
MODEL SILL 1/16
NATURAL SIZE
ADJUSTABLE
TAILGATE
WEIR BOX
BAFFLES
72.9'
4 SPACES AT 10.0' = 40.0'
31.0'
LAYOUT OF APPARATUS FOR FLUME TESTS
3.13'
1:3
1:3
0.44'
0.94'
0.5'
1:3
TYPE A-7
B-7
C-7
NOTE:
TYPE D-7 & D-12 SAME AS
TYPE C-7 & C-12 WITH ENDS
REVERSED.
3.13'
1:3
1:3
0.75'
0.94'
0.5'
1:3
TYPE A-12
B-12
C-12
CROSS SECTIONS OF MODEL SILLS
ST. CLAIR RIVER
SUBMERGED SILL TESTS
IN
STANDARD FLUME
U.S. WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI
SUBMITTED:
ASSISTANT ENGINEER
RECOMMENDED:
2 ND LIEUTENANT C.E.
APPROVED:
1ST LIEUTENANT C.E.
DRAWN BY W.A.M.
TRACED BY W.A.M.
CHECKED BY J.S.M.

PLATE 1

of the water-surface elevations in each of the piezometer buckets and of the head on the weir. The mean of these ten readings for each gage was taken as its value for the run.

17. Next the valve was closed, the flume was drained, and the sill to be tested was set carefully in place and shimmed up until it was level. The test was then resumed, with the same discharge as used in the preceding run. The elevations of the ends of the tailgate, which had not been disturbed, were checked, and another series of ten sets of readings of the hook gages was secured. The means of these values were taken as the values for the second run. The flow was then readjusted more nearly to the desired value (if it had varied slightly from that value during the second run), the elevation of the tailgate was rechecked, and the run was repeated. After this third run the flow was again stopped, the sill was removed, and a fourth run was made in the open flume to check the results of the first. Such a set of four runs was made for each of the sills tested. Comparisons between the water-surface elevations for the runs with and without the sills indicated the amount of backwater produced.

18. During the preliminary runs it was found that there was never any appreciable difference between the readings of the point gages and the corresponding readings of the hook gage in the piezometer buckets; thereafter the point gages were not read regularly, but were used occasionally to check the hook gage.

Results:

19. The average backwater effects of the different types of sills tested in the flume are presented in Table 1. The data from which the averages were obtained are presented at length in Table 1, Appendix C.

TABLE 1

Average Backwater Effects of Sills Tested in Standard Flume

Runs	Sill Tested			Backwater Effect in Flume
	Type	Upstream Face	Downstream Face	*Feet*
1-4	A-12	1:3*	1:3	0.0010
5-8, 33-34	D-12	1:3	Vertical	0.0021
9-12	C-12	Vertical	1:3	0.0072
13-16	B-12	"	Vertical	0.0071
17-20, 37-40	A-7	1:3	1:3	0.0007
21-24, 35-36	D-7	1:3	Vertical	0.0007
25-28	C-7	Vertical	1:3	0.0037
29-32	B-7	"	Vertical	0.0026

NOTE:—The sills were constructed to a 1:16 scale and the velocity in the flume was reduced to 1/4 the mean velocity in nature or 0.78 foot per second. The depth of submergence corresponded to 30 feet in nature. The results are given in feet observed in the flume. To transfer to corresponding effects in nature, the backwater effect should be multiplied by 16.

* The vertical distance is given first in all slope ratios used in this report.

20. It is to be noted that the observed backwater effects are very small, and that even with the most careful work the incidental and unavoidable errors in observation are large relative to the differences measured. Considering the circumstances, the results of the experiments appear to be about as consistent and accurate as it is practicable to obtain them.

21. Of the four types of sills tested (see Plate 1), those of Type A produced the least backwater, and those of Type D had but little more effect. Type C, with a vertical upstream and a sloping downstream face, was found to have much greater backwater effect than Types A or D, and a slightly greater backwater effect than Type B, which had both faces vertical. The results indicate that a sill with a vertical upstream face is much more effective in creating backwater than a sill with a sloping front face. The downstream face does not appear to have a marked effect.

22. For those tests in which the dimensions and other factors were the same, the results of the University of Michigan experiments were checked reasonably well. As was deduced from the Michigan data, it appears that the flow over such deeply submerged sills differs fundamentally from the flow over the usual dam or broad-crested weir, and that the backwater effect is primarily a function of the turbulence produced by the submerged obstruction. The comparative heads, or backwater effects, for these sills seem to bear little relation to the corresponding heads that would be observed if the same sills were used as ordinary broad-crested weirs.

Model of St. Clair River

Scales: 1:30 Vertical, 1:100 Horizontal

23. Since the flume tests were run for average and idealized conditions, it was not expected that their results necessarily would correspond to those that might be realized in the river. It was decided, therefore, to build a model of the river channel for further study. The flume tests indicated that the backwater effects of certain of the proposed types of sills would be small. To facilitate the measurement of small vertical differences, a distorted model of the St. Clair River was constructed, which was designed to indicate the comparative effects of the different types of sills under the conditions which would be encountered in nature.

24. There were two types of flow to be considered in this model—flow over the sills and flow as governed by the frictional resistance of ordinary open channels. In order to satisfy both the Froudian relationship and those derived from open channel flow formulas, it was necessary to make the vertical scale a definite function of the horizontal scale. The largest practical horizontal scale for the model was 1:100, and from this the necessary vertical scale was computed to be 1:30.

The Model:

25. A model of the outlet of Lake Huron, and of the upper St. Clair River down to a point some 2,000 feet below the mouth of

Black River, was constructed of concrete to a horizontal scale of 1:100 and to a vertical scale of 1:30 (see Plate 2). Ten gages were placed in this model, corresponding in location to gages on Lake Huron and along the St. Clair River. These gages were piezometer openings carefully set flush with the surface of the model, and connected by pipes to a central gage pit, where a row of ten gage buckets was so arranged under a slide rod that the elevation of the water surfaces in each bucket could be read by the same hook gage. Water entering the model from the reservoir was measured by a 5-foot rectangular suppressed weir. A long tailgate was provided to adjust the water-surface elevation at the lower end of the model.

26. Eight vertical-faced sills, placed at locations recommended by the St. Lawrence Board (see Plate 3), were so constructed of wood that they could easily be set in place or removed. Later, concrete blocks were made so the sills could be given different side slopes. Plate 4 shows in detail the cross-sections of all the various types of sills tested. The crest elevations of the sills were obtained from the U. S. Lake Survey Office, and are given below in Table 2.

TABLE 2

Elevations of Crests of Sills Used in St. Clair Model

Horizontal Scale 1:100; Vertical Scale 1:30

Sill Number	Elevation Standard Low Water in Feet M. S. L. at Site of Sill, as Read from Profile	Depth of Crest of Sill in Feet below Standard Low Water	Elevation Crest of Sill in Feet M. S. L.
1	577.72	31.5	546.22
2	577.73	30.0	547.73
3	577.74	30.0	547.74
4	577.75	30.0	547.75
5	577.72	30.1	547.62
6	577.69	33.5	544.19
7	577.66	31.6	546.06
8	577.62	30.0	547.62

Procedure:*

27. The preliminary tests established the fact that a greater quantity of water was required to reproduce the natural profile than was indicated by the discharge scale obtained from similitude relationships. This meant that the concrete bed of the model was too

* Three discharges were furnished by the U. S. Lake Survey to be simulated in the model tests. The mean discharge for open-river conditions is 194,000 cubic feet per second and the approximate extremes in ice-free flow are 170,000 cubic feet per second and 220,000 cubic feet per second.

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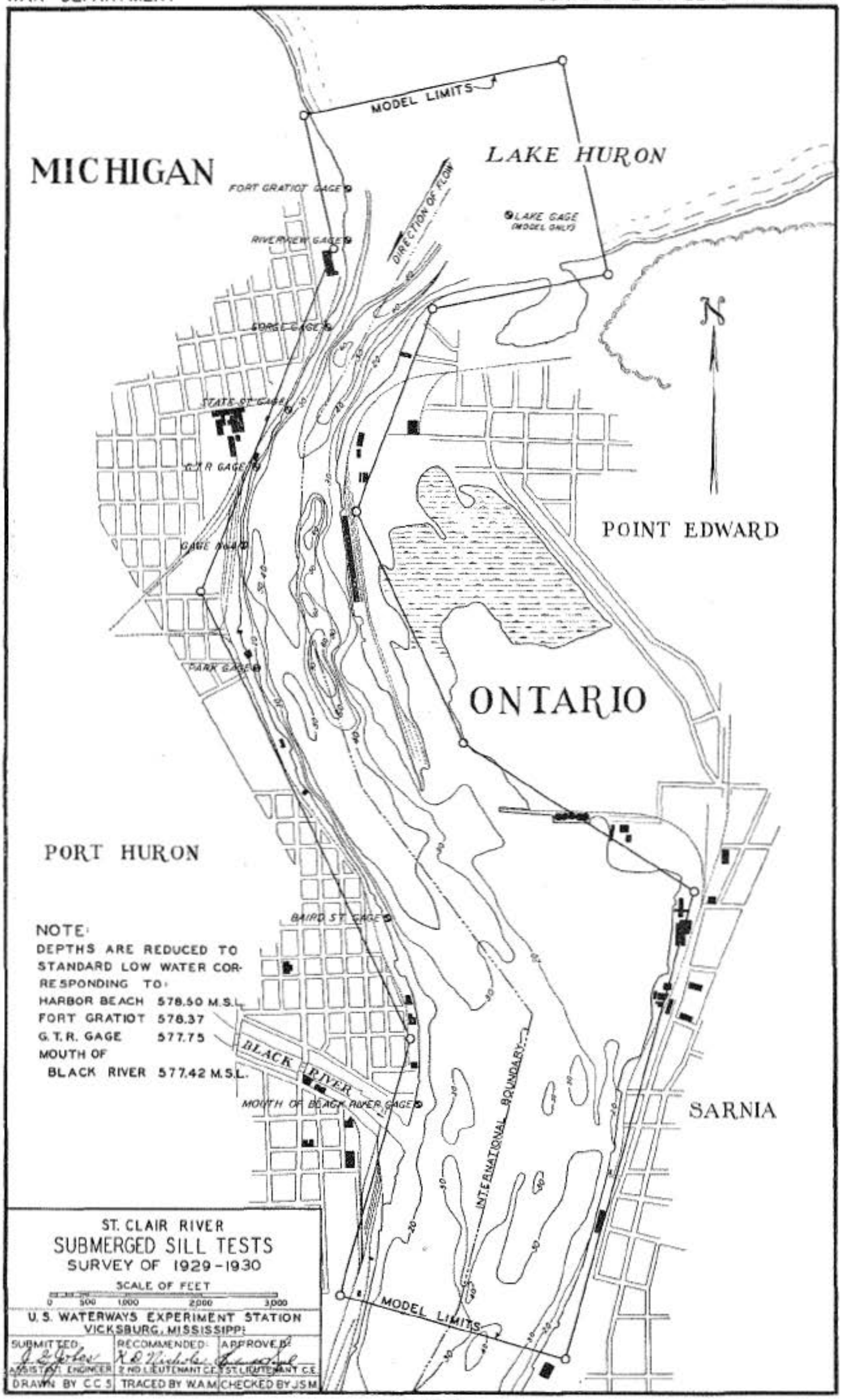


PLATE 2

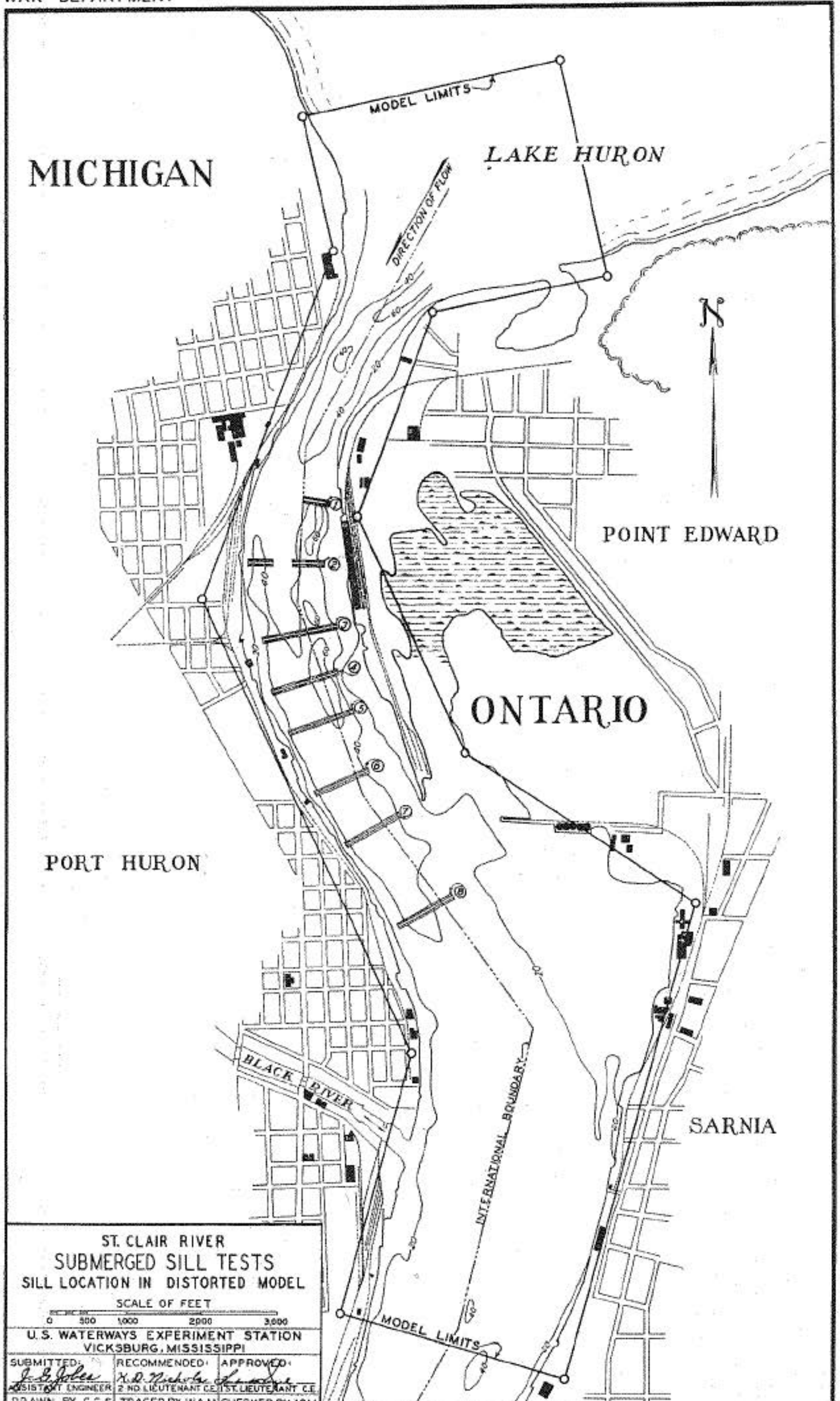

MICHIGAN
LAKE HURON
MODEL LIMITS
DIRECTION OF FLOW
N
POINT EDWARD
ONTARIO
PORT HURON
BLACK RIVER
INTERNATIONAL BOUNDARY
SARNIA
MODEL LIMITS
ST. CLAIR RIVER
SUBMERGED SILL TESTS
SILL LOCATION IN DISTORTED MODEL
SCALE OF FEET
0 500 1,000 2000 3,000
U.S. WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI
SUBMITTED:
ASSISTANT ENGINEER
RECOMMENDED:
2ND LIEUTENANT C.E.
APPROVED:
1ST LIEUTENANT C.E.
DRAWN BY C.C.S.
TRACED BY W.A.M.
CHECKED BY J.S.M.

PLATE 3

smooth to simulate properly the much rougher bed of the river. Accordingly, the roughness of the model was increased, by applying a thin coating of hot tar, into which were thrown sharp pieces of finely-crushed slag, resulting in a "pebbledash" surface. By this treatment the quantity of water required by the model was much reduced, although it was still necessary to use more than the quantity indicated by similitude formulas. To further reduce the discharge scale would have required such excessive roughness that the cross-section would have been appreciably changed. Thus, instead of a discharge scale of 1:16,430 as obtained by similitude re-

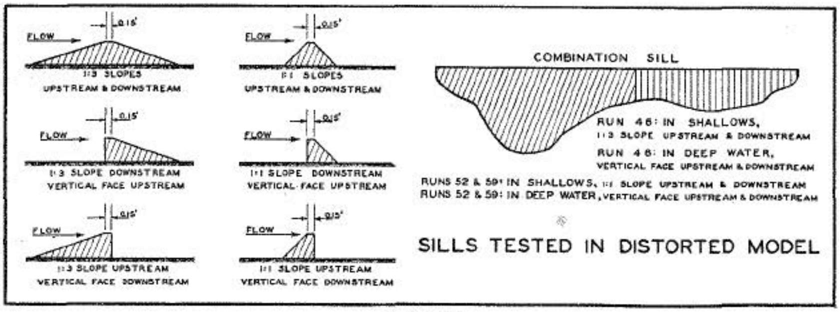


PLATE 4

lationships for the model, a compromise discharge scale of 1:14,400 was used. This resulted in higher velocities in the model than should have been employed to obtain dynamic similarity, and consequently greater backwater effects were produced by the sills than normally should have been obtained.

28. After deciding that it was impracticable to further reduce the discharge scale, regular tests were conducted as follows:

(a) *Run with no sills.*

The model discharge and the tailgate setting were varied until the water-surface elevations in the Lake (at the upper end of the model), and at the Black River gage (at the lower end of the model), stood at the proper values for the particular flow that was being simulated. The elevations of the ends of the tailgate were observed and recorded. A series of ten readings was then made, as rapidly as possible, of the water-surface elevations at each of the ten gages and of the head on the weir. The means of these readings were taken as the values for the run.

(b) *Run with sills.*

In this case the model discharge and the tailgate setting were made the same as in the preceding open-river run. The sills to be tested were set in place and carefully

brought to grade with an engineer's level. After water had run through the model long enough for conditions to become steady, tailgate elevations were observed and recorded, a series of ten readings of the gages was taken as before, and the means of these readings were used as the values for the run.

The backwater effect for any set of sills tested was then found by comparing the observed differences in elevation between the upper and lower gages in the model for the two runs.

Results:

29. The average backwater effects of the different types (see Plate 4) and combinations of sills tested are presented here in Table 3. The data from which the averages were obtained are presented at length in Table 2 of Appendix C.

TABLE 3

Average Backwater Effects of Sills As Observed in St. Clair Model

Vertical Scale 1:30; Horizontal Scale 1:100.

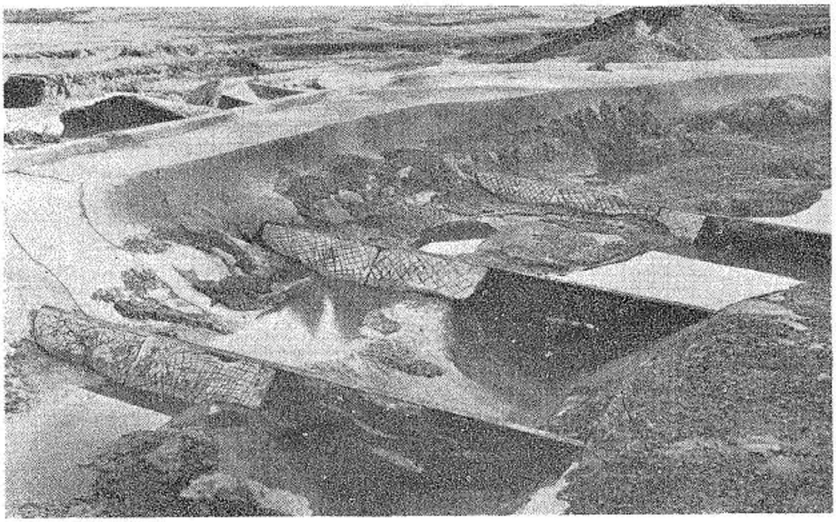
Numbers of Sills	Type of Sill		Backwater Effect, Feet in Nature, Discharge Corresponding to:		
	Upstream Face	Downstream Face	170,000 c. f. s.	194,000 c. f. s.	220,000 c. f. s.
1-8	Vertical	Vertical	0.53	0.80	0.81
1-8	1:3	1:3		0.21	
1-8	1:1	1:1		0.21	
2-7	Vertical	Vertical	0.49	0.67	
2-5, 7	"	"		0.58	0.63
2-5	"	"	0.30	0.51	0.52
2, 4, 6, 8	"	"		0.41	
2, 6-8	"	"		0.29	
1-8	Part Vert. / " 1:3	Part Vert. / " 1:3		0.45	
1-8	Part Vert. / " 1:1	Part Vert. / " 1:1		0.73	
1-8	Vertical	1:3		0.71	
1-8	1:3	Vertical		0.37	
1-8	Vertical	1:1		0.84	
1-8	1:1	Vertical		0.59	
1-8	Vertical Crests Lowered 5′	"		0.45	

PLATE 5

DISTORTED MODEL OF ST. CLAIR RIVER.

Above: *General view of model in operation, looking downstream.*

Below: *Looking upstream, with sill No. 5 in foreground. Shows sills for Run No. 52, with vertical faces in deep sections, and 1:1 sloping faces in shallow sections.*



30. The backwater effects listed in Table 3 are to be regarded as comparative only. As mentioned before, the absolute backwater effects are somewhat large, due to the high velocities used in the model, but the relative effects of different types and combinations are expressed by these data. A general tendency shown by the results obtained from this model is that the backwater effect of the sills increases as the discharge of the river increases. Sills with vertical upstream faces are seen to be more effective than those of other types. The slope of the downstream face does not appear to have much influence on the backwater produced.

31. It was also noted that the pronounced eddy on the Canadian side, opposite the Park Street gage, was largely broken up by the sills. The reduction in size of this eddy would tend to increase the discharge capacity of the channel, and so counteract to some extent the desired effect of the sills.

Model of St. Clair River

Scales: 1:100 Vertical, 1:100 Horizontal

32. Since there were several unsettled questions about the advisability of accepting at their observed values all the results from the distorted model for this particular kind of problem, it was decided that tests on an undistorted model should supplement those on the distorted model. The choice of proper side slopes for the sills in the distorted model was an especially troublesome question. By using the model scales, a 1:3 slope in nature would become about a 1:1 slope in the model, but there was always some question as to whether the proper hydraulic effect would be obtained in this particular case by such distortion. Then, when it was found to be impracticable to secure proper velocities in the distorted model, the necessity for an undistorted model became more evident. Accordingly, the model was reconstructed with both vertical and horizontal scales of 1:100. This reduced the exactness with which differences in elevation could be simulated, but it also eliminated the effects of distortion.

The Model:

33. The undistorted model covered the same area as did the distorted model, reproducing the St. Clair River from the lower end of Lake Huron to a point some 2,000 feet below the mouth of Black River, as indicated on Plate 2. Water circulated by a pump was supplied to the model from a constant-head tank, and was measured by a triangular weir. The same ten gages were used as before.

Sills:

34. Sills were used again at the same locations proposed by the St. Lawrence Board. It developed, as the tests progressed, that other locations for the sills might be of advantage, and these are

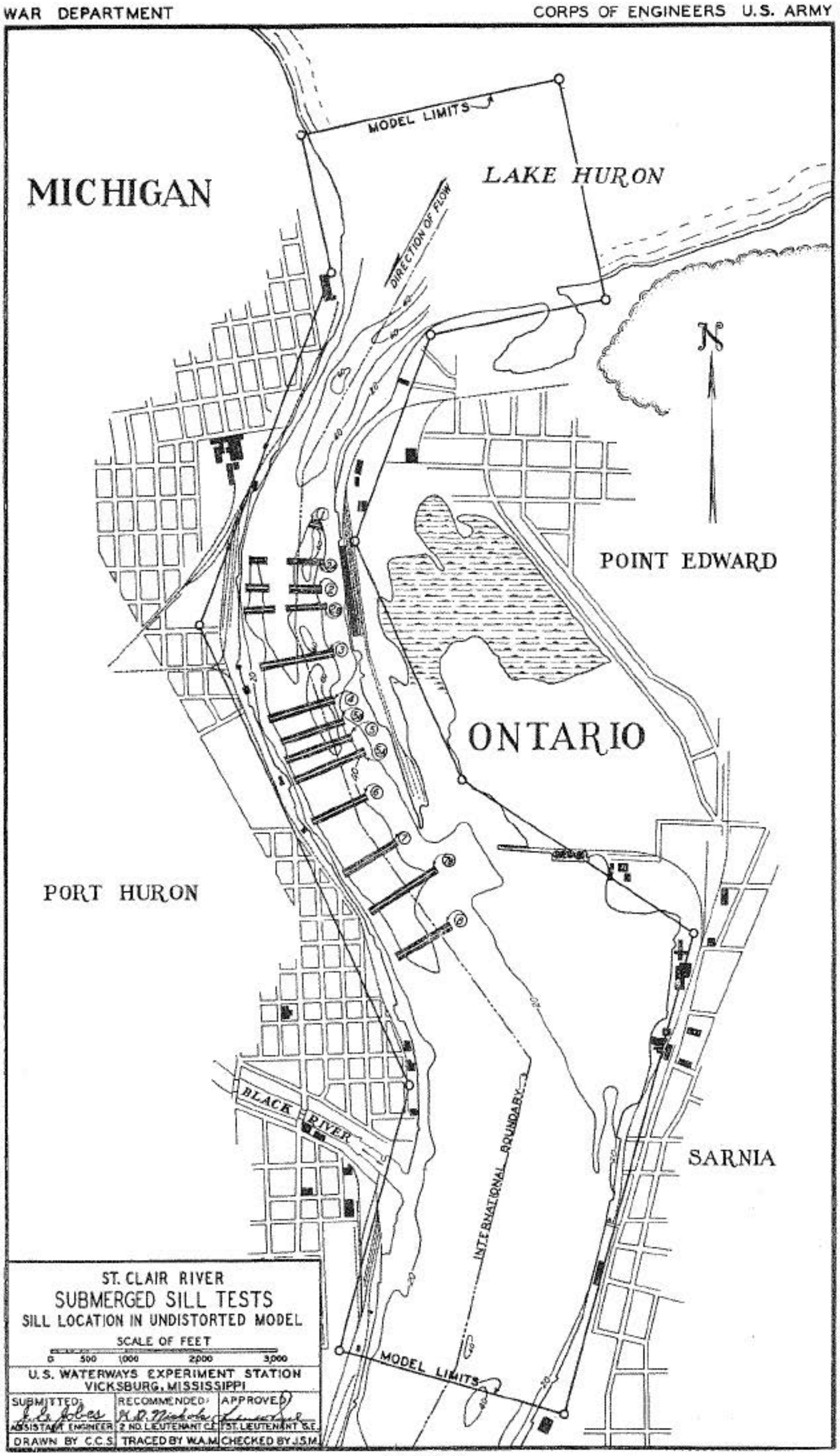

WAR DEPARTMENT
CORPS OF ENGINEERS U.S. ARMY
MODEL LIMITS
LAKE HURON
MICHIGAN
DIRECTION OF FLOW
POINT EDWARD
ONTARIO
PORT HURON
BLACK RIVER
INTERNATIONAL BOUNDARY
SARNIA
MODEL LIMITS
ST. CLAIR RIVER
SUBMERGED SILL TESTS
SILL LOCATION IN UNDISTORTED MODEL
SCALE OF FEET
0 500 1000 2000 3000
U.S. WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI
SUBMITTED:
ASSISTANT ENGINEER
RECOMMENDED:
2 ND. LIEUTENANT C.E.
APPROVED:
1ST. LIEUTENANT C.E.
DRAWN BY C.C.S.
TRACED BY W.A.M.
CHECKED BY J.S.M.

PLATE 6

shown on Plate 6. The sills were made with various cross-sections, some being the same as those previously proposed and tested, and others being new cross-sections, suggested by the Lake Survey Office, and the U. S. Engineer Office at Detroit as being more economical to construct. Cross-sections of all sills tested are shown on Plate 7, and crest elevations of sills are given in Table 4.

TABLE 4

Elevations of Crests of Sills Used in St. Clair Model

Vertical Scale 1:100; Horizontal Scale 1:100

Sill Number	Location—No. of Section in 1929 Survey	Elevation of Standard Low Water in Feet M. S. L. at Site of Sill	Depth of Crest of Sill in Feet below Standard Low Water	Elevation of Crest of Sill in Feet M. S. L.
1	320	577.75	40.70	537.05
2	317	577.76	30.70	547.06
3	314	577.76	30.00	547.76
4	312	577.75	31.10	546.65
5	310	577.71	33.20	544.51
6	307	577.76	33.50	544.26
7	304	577.62	34.80	542.82
8	300	577.55	30.60	546.95
2-A	318	577.76	33.00	544.76
2-B	316	577.76	30.00	547.76
5-B	311	577.73	35.00	542.73
5-A	309	577.70	33.25	544.45
7-B	302	577.59	30.00	547.59

NOTE:—For Sills 1-8, the values given do not agree exactly with those given in Table 2, which were used in the distorted model. The values in Table 4 were furnished by the U. S. Lake Survey Office, in a letter dated October 24, 1933, while the values in Table 2 were taken from earlier surveys and reports.

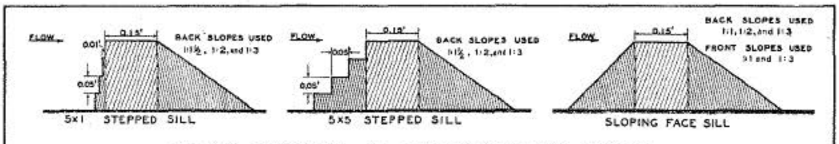
Procedure:

35. The procedure used in running tests on the undistorted model was essentially the same as that used for the distorted model. In this case it was also found that the discharge required to reproduce the natural profile in the unroughened model was greater than that indicated by the Froudian similitude relationship, $q = l^{\frac{5}{2}} = \frac{1}{100,000}$. However it was easily possible, by a slight roughening of the bed of the model, to obtain the correct water-surface elevations using the theoretical discharge. After a number of trial runs had been made it was found that this roughness was most satisfactorily ob-

tained by the use of several pieces of ¼-inch mesh galvanized wire screen, laid flat on the bed of the model. These screens could be removed when the model was cleaned, and replaced in the same positions without change in effect. They were used in all the runs for which data are given in the following pages, and the theoretical discharge scale of 1:100,000 was strictly followed.

36. The test runs may be divided into two classifications, as follows:

(a) *Runs without sills,* in which the model simulated the existing unobstructed river channel.



SILLS TESTED IN UNDISTORTED MODEL

PLATE 7

The model discharge was found by multiplying the discharge scale (q = 1:100,000) by the natural discharge. The tailgate was adjusted to reproduce, as nearly as possible, the natural water-surface profile. As soon as the flow had become steady, a series of ten readings was made, as rapidly as possible, of the water-surface elevations in Lake Huron, at the upper end of the model, and at the Black River gage, at the lower end. The means of these two sets of ten readings for each gage were taken as the values for the run.

(b) *Runs with sills*, in which the model simulated the river channel with various proposed sills installed.

After the observations noted in (a) had been made, and without shutting down the flow of water or changing the tailgate setting, any desired group of sills was set in place in the model channel. Again, after the flow had become steady, a series of ten readings was made of the water-surface elevations at the Lake and at the Black River gages, and the means of these readings were taken as the values for the run.

The backwater effect of any particular set of sills was found, as before, by comparing the runs made with and without sills.

Results:

37. The average backwater effects of the different types (see Plate 7) and combinations of sills tested are given in Table 5. From the mass of data from which these averages were obtained, certain representative runs were selected as being typical, and data for these runs are given in detail in Table 3 of Appendix C.

TABLE 5

Average Backwater Effects of Sills As Observed in St. Clair Model
Vertical Scale 1:100; Horizontal Scale 1:100.

Numbers of Sills in Model	Type of Sill		Backwater Effect, Feet in Nature, Discharge Corresponding to:		
	Upstream Face	Downstream Face	170,000 c. f. s.	194,000 c. f. s.	220,000 c. f. s.
1-8	Vertical	Vertical	0.47	0.52	0.61
"	"	1:1			0.59
"	"	1:3			0.62
"	1:1	1:1			0.49
"	1:3	1:3			0.28
"	1x5	1:1½			0.60
"	1x5	1:2	0.48	0.52	0.59
"	1x5	1:3	0.46	0.45	0.52
"	5x5	1:1½			0.47
"	5x5	1:2			0.47
"	5x5, 1:1	1:2			0.43
1-8, 7B	1:1	1:2			0.49
"	1x5	1:2	0.52	0.61	0.62
"	5x5	1:2	0.46	0.43	0.51
"	5x5	1:3			0.49
1-4, 5A, 5B, 6-8	1x5	1:2	0.53	0.61	0.67
"	5x5	1:2	0.44	0.53	0.55
1, 2A, 2B, 3-8	5x5	1:2			0.48
"	5x5	1:3			0.49
1, 2A, 2B, 3-8, 7B	5x5	1:3			0.50

38. The data listed in Table 5 exhibit the same general tendencies that were noted in previous tests. The backwater effects of the various sills are seen to increase with the discharge. The type of upstream face used for the sill obviously has more influence on the backwater effect than does the downstream face. Sills with vertical or 5x1 stepped upstream faces produce greater backwater effects than sills with sloping or 5x5 stepped faces. As would be expected, extra sills in the deeper parts of the channel cause greater effect than extra sills in shallower parts. It appears that there are various combinations of types and numbers of sills that would provide the desired backwater of 0.54 foot.

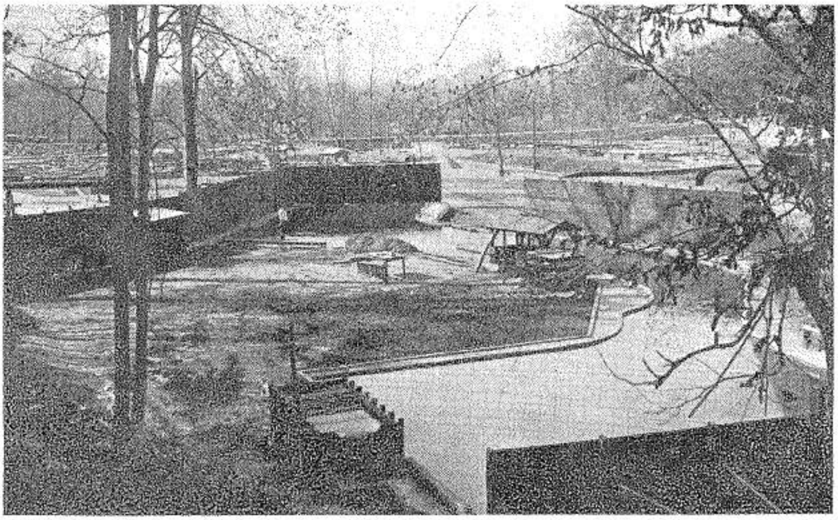
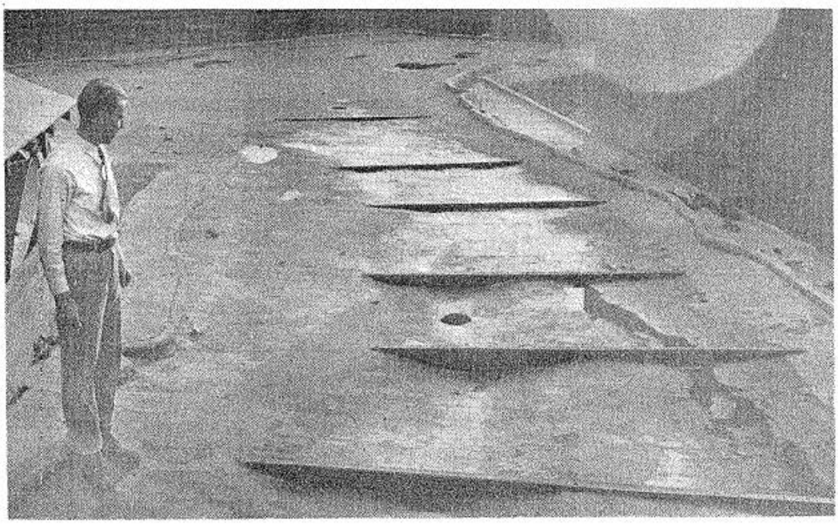


PLATE 8

UNDISTORTED MODEL OF ST. CLAIR RIVER.

Above: General view of model in operation, looking downstream. Walls were erected to keep wind from affecting the experiments.

Below: Looking downstream, with sill No. 3 in foreground. Shows sills with stepped upstream faces



Effect of Silting:

39. Although the amount of sediment carried by the St. Clair River is extremely small, there is nevertheless some possibility of silt being deposited in the pockets between the sills, and a question was raised as to the effect of such silting upon the backwater produced by the sills. Tests were run to secure an indication of the effect of an extreme amount of silting, by operating the model with the bed filled with sand up to the level of the sill crests. A comparison between runs made with the beds so filled with sand and runs made with an open-river channel indicated a backwater effect in Lake Huron corresponding to 0.18 foot in nature, when the St. Clair River was discharging 220,000 c. f. s.

Effect of Higher Sills:

40. In the distorted model the elevations of the crests of the sills (Table 2) were generally higher than those used in the undistorted model (Table 4), which were made to agree with revised elevations furnished by the U. S. Lake Survey Office. In order to compare more directly the results obtained from the two models, tests were run on the undistorted model with the sills raised to the elevations given in Table 2. A backwater effect corresponding to 0.64 foot in nature for a discharge of 194,000 c. f. s. was observed in the model for sills 1-8 with both faces vertical. For the same sills, but with higher comparative discharges, the distorted model indicated an effect of 0.80 foot (Table 3).*

Surface Currents:

41. As was the case with the distorted model, it was observed in these tests that the eddy on the Canadian side, opposite the Park Street gage, was greatly reduced when the sills were set in place. Plate 9 shows the extent of the eddy, as observed by tracing the paths of surface floats in the model, with and without sills, for a discharge corresponding to 194,000 c. f. s. in the river. Similar observations were made for river discharges of 170,000 and 220,000 c. f. s., but the appearance of the resulting eddy diagrams was virtually identical with Plate 9, so they are not shown here.

Velocity Distributions:

42. Explorations with a Bentzel velocity tube were made at the sites of sills 3, 5, and 7, to see what changes might be observed in the magnitude and distribution of velocities both when the channel was unobstructed and when the sills were in place. The observed velocities are plotted in the diagrams of Plate 10. These diagrams show that, for the channel without sills, the velocities were quite unevenly distributed, and that after the sills were in place the velocity distribution became more uniform. Therefore, although mean velocities at the sites of the sills were necessarily increased, maximum velocities were increased to a lesser extent.

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* For a further comparison of results obtained from the distorted and undistorted models, see Appendix D

Summary of Results

Efficiency of Different Types of Sills:

43. The model tests all indicated that the amount of backwater varied greatly with changes in sill cross-sections. The type of upstream face was the important factor in determining the efficiency of the sill, while the type of downstream face had but little effect, within the range of conditions tested. Although it might be

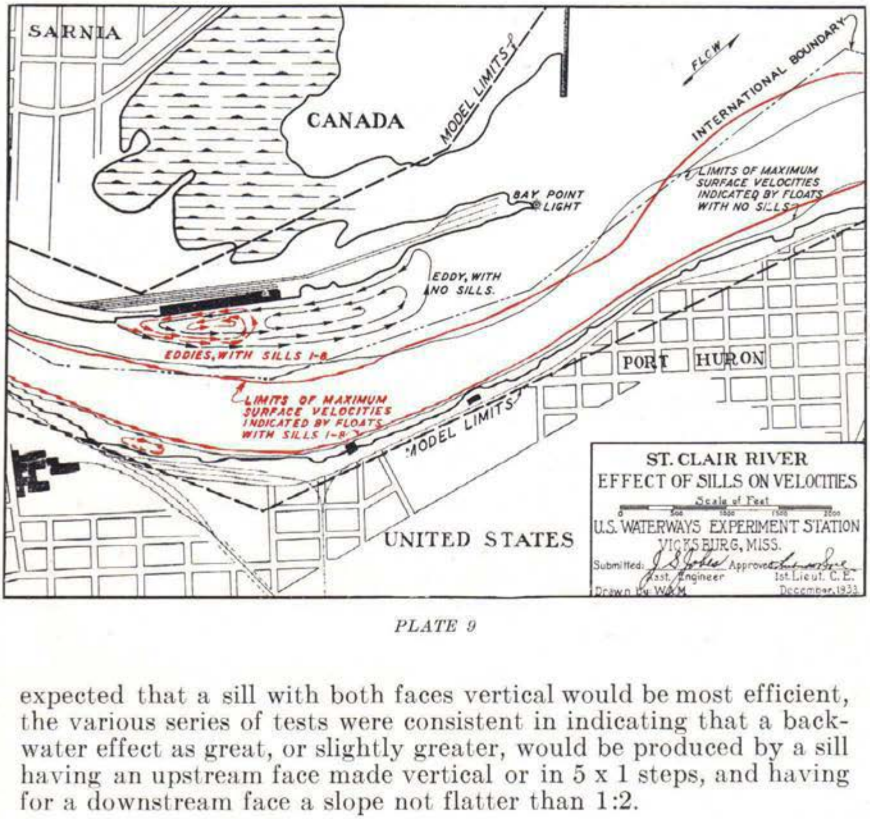
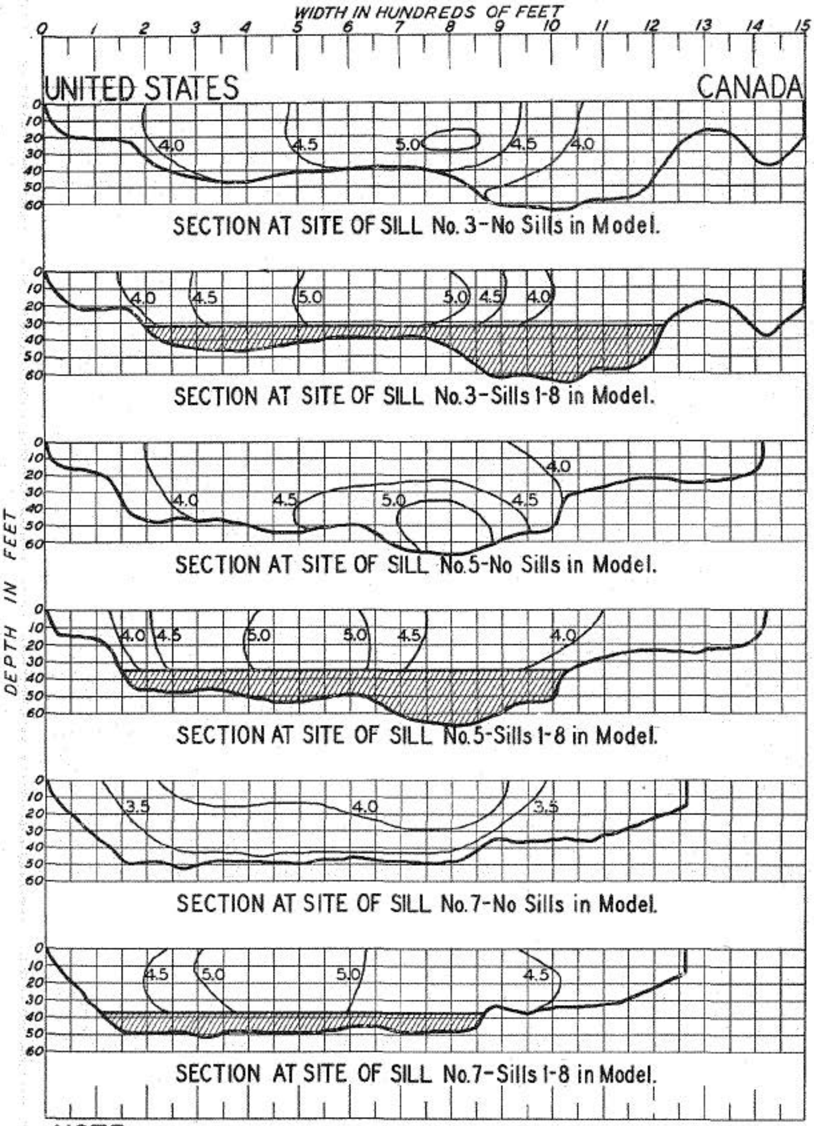


PLATE 9

expected that a sill with both faces vertical would be most efficient, the various series of tests were consistent in indicating that a backwater effect as great, or slightly greater, would be produced by a sill having an upstream face made vertical or in 5 x 1 steps, and having for a downstream face a slope not flatter than 1:2.

Variation of Backwater Effect With Discharge:

44. The model tests were consistent in indicating that the backwater produced by any particular set of sills was greater for the higher than it was for the lower discharges, although the difference was not very great for the range in discharge encountered in the St. Clair River. Tests made on 1:100 scale model sills in a flume (Appendix A) indicated that, for the same depths of submergence, the backwater effect of a sill or combination of sills varied as the square of the velocity in the unobstructed channel.



NOTE:
VELOCITIES REPRESENT THOSE IN NATURE IN FT. PER SEC.
FLOW IN RIVER 194,000 C.F.S.
SCALES, d=1/100 l=1/100

ST. CLAIR RIVER
SUBMERGED SILL TESTS
VELOCITIES OBSERVED IN MODEL
U.S. WATERWAYS EXPERIMENT STA.
VICKSBURG, MISSISSIPPI.

SUBMITTED:	RECOMMENDED:	APPROVED:
J. G. Jobes	K. D. Nichols	
ASST. ENGR.	2nd. LIEUT. C. E.	1st. LIEUT. C.E.
DRAWN, W.M.	TRACED, W.A.M.	CHECK, J.G.J.

PLATE 10

Magnitude of Backwater Effect:

45. The results of tests on the undistorted model (Table 5), which are believed to be reliable, indicate that the desired backwater of 0.54 foot can be obtained by the construction of various types and combinations of sills. It is possible to secure the 0.54 foot backwater with eight sills in the locations proposed by the St. Lawrence Board, but it would be necessary to use a different cross-section from that originally proposed. The data in Table 5 and on Plate 6, showing observed backwater effects and locations of sills tested, respectively, furnishes sufficient information to allow the selection of the best combination of sills to produce any desired effect.

Effect of Variation in Spacing of Sills:

46. It was found from the flume experiments described in Appendix A that the total backwater effect of one or more sills varied directly with the number of sills. The effect per sill was not changed when the spacing of sills in the flume was reduced from 7 feet to 3½ feet, which would correspond to 700 feet and 350 feet in nature. It should be noted, however, that this result was indicated by flume tests, and that it might not hold for the conditions that occur in the river, where the velocity distributions may be materially changed by the construction of sills.

HERBERT D. VOGEL

1st Lieutenant, Corps of Engineers
Director, U. S. Waterways
Experiment Station

APPENDIX A

FLUME TESTS ON 1:100 MODEL SILLS

Synopsis

1. In addition to the tests made on the two outdoor models and in the large indoor flume, which are described in the body of this report, certain supplementary experiments were made in a tilting flume. The results of these flume tests indicate that:

(a) Sills with vertical upstream faces produce a greater backwater effect than sills with sloping upstream faces.

(b) Within the range of conditions tested, the backwater produced by an individual sill is not affected by the proximity of other sills.

(c) The principles of hydraulic similitude apply to these sills.

Purpose of Experiments

2. These experiments were undertaken in order to obtain more information about the behavior of deeply submerged sills, particularly with regard to the points mentioned in the synopsis. Since it was very much simpler and easier to make tests in the flume, they were made whenever practicable to supplement the concurrent tests on the undistorted outdoor river model.

Apparatus

3. A general sketch of the apparatus used is shown on Plate 11. Water, measured by a calibrated triangular weir, flowed down a flume 2.4 feet wide, 0.85 foot deep, and 45 feet long, in which model sills were placed. A movable tailgate at the lower end of the flume was used to adjust the depth of the water to any desired amount. Piezometer openings, at 7-foot intervals in the side of the flume, were connected with hook gage wells where water-surface elevations could be measured. A movable point gage mounted on a frame sliding on rails at the sides of the flume made it possible to determine water levels at any desired intermediate points.

First Series of Experiments

Procedure:

4. Tests were made to find the backwater produced by 1:100-scale models of individual sills of various cross-sections, as shown on Plate 11. The model sills tested in this series were all 0.12 foot high and the depth of water in the flume was maintained at 0.42 foot, in simulation of a 12-foot sill in a 42-foot river channel. The velocities in the flume were varied to simulate the different velocities that would be encountered at various locations in the river. The results of these tests are presented in Table 1 of this appendix.

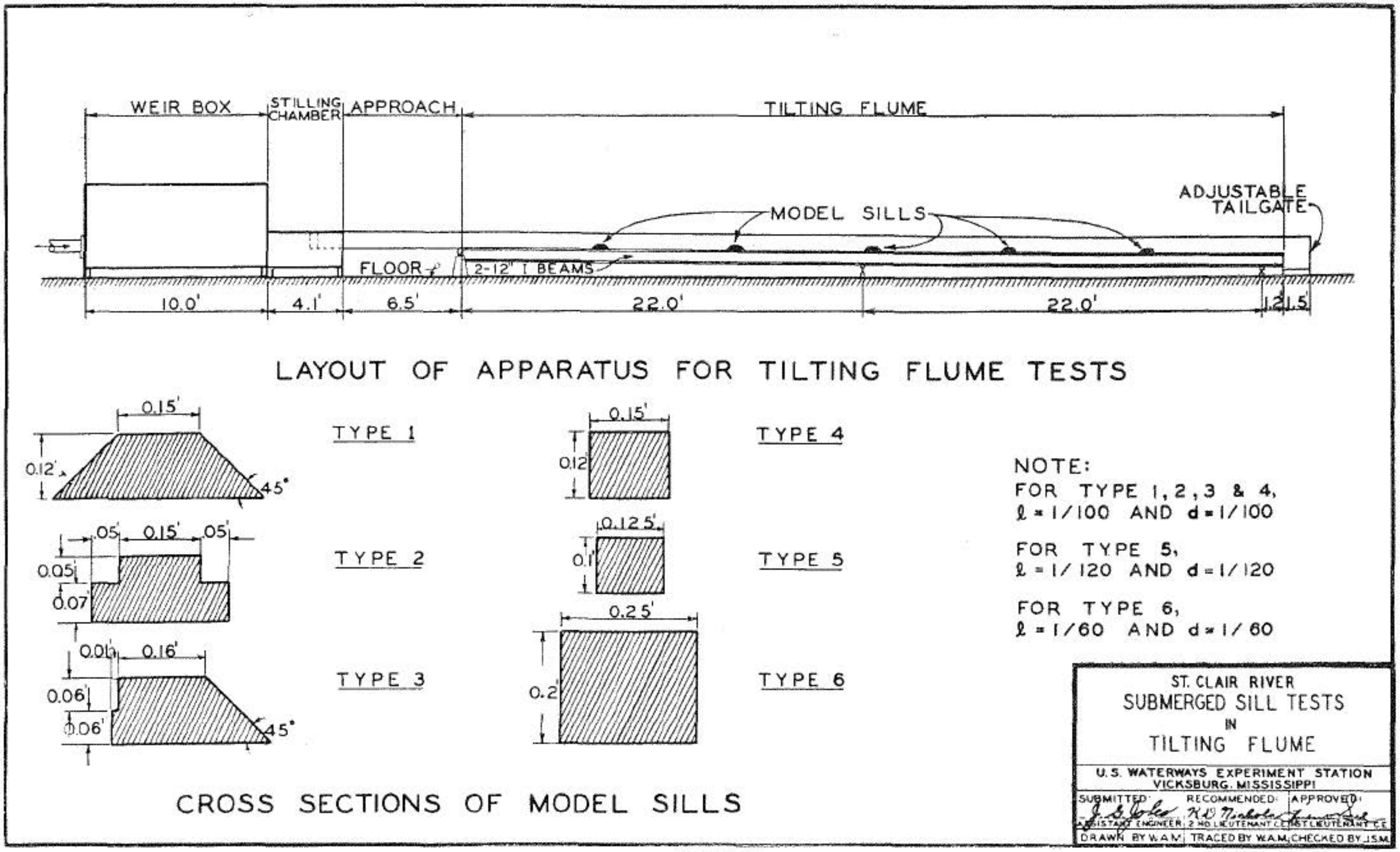

WEIR BOX
STILLING CHAMBER
APPROACH
TILTING FLUME
ADJUSTABLE TAILGATE
MODEL SILLS
FLOOR
2-12" I BEAMS
10.0'
4.1'
6.5'
22.0'
22.0'
1.2
1.5
LAYOUT OF APPARATUS FOR TILTING FLUME TESTS
TYPE 1
TYPE 2
TYPE 3
TYPE 4
TYPE 5
TYPE 6
NOTE:
FOR TYPE 1, 2, 3 & 4, ℓ = 1/100 AND d = 1/100
FOR TYPE 5, ℓ = 1/120 AND d = 1/120
FOR TYPE 6, ℓ = 1/60 AND d = 1/60
CROSS SECTIONS OF MODEL SILLS
ST. CLAIR RIVER
SUBMERGED SILL TESTS
IN
TILTING FLUME
U. S. WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI
SUBMITTED:
RECOMMENDED:
APPROVED:
ASSISTANT ENGINEER
2 ND LIEUTENANT C.E.
1ST LIEUTENANT C.E.
DRAWN BY W.A.M.
TRACED BY W.A.M.
CHECKED BY J.S.M.

PLATE 11

Results:

5. It may be seen from the data in Table 1 that the backwater effect is dependent on the shape of the sill cross-section in the same general way as was indicated by the river model tests. It was found that, for the same size of sill and depth of water, the backwater effect varies as the square of the mean velocity in the channel approaching the sill. In other words, the value of K (see Appendix B) remains sensibly constant for the same sill when water flows over it at different velocities.

Second Series of Experiments

Procedure:

6. This series of tests was made to find the effect on the action of one sill of placing others near it. First, five sills were set in the flume at 7-foot intervals, and the total backwater effect was measured. Then, the upstream sill was removed, and the new backwater effect was measured. Then the fourth, third, and second sills were removed successively, and the backwater was measured after each removal. This procedure was followed for two types of sills, using two velocities for each type. Finally, nine sills were set in the flume at 3½-foot intervals, and the backwater was measured as they were successively removed. Results of these tests are listed in Table 2 of this appendix.

Results:

7. It was found that the backwater effect of one sill was not reduced when other sills were set adjacent to it. The tests showed, very consistently, that the backwater effect of n sills was equal to n times the effect of one sill.

Third Series of Experiments

Procedure:

8. These tests were made to check the applicability of the theory of hydraulic similitude to the flow over submerged sills. Models of a sill 12 feet high in a 42-foot channel were made to scales of 1:60, 1:100, and 1:120. Using the proper depths of water in the model flume, and velocities corrresponding to 4 feet per second in nature, observations of backwater effect were made for one, two, and three sills, for each of the three sizes of sills. Results of these tests are given in Table 3 of this appendix.

Results:

9. In Table 3, the observed backwater effects for the model sills have been transformed to the corresponding effects in nature by dividing the model effects by the scale ratio, in accordance with the theory of similitude. It is to be noted that the backwater effects, as expressed in natural values, show but little variation—in

fact, what variation does exist can reasonably be attributed to unavoidable errors in the observation of the very small differences measured in the model flume. Therefore, as far as can be predicted from these tests on models of different scales (1:60, 1:100, and 1:120), the relations of similitude apply.

Discussion of Similitude

10. A further check on the validity of similitude as applied to such sills is obtained from a comparison of these data with those for the earlier flume tests on 1:16 scale model sills. Sill B-12 (see Table 1 of main report) was of similar shape, and was tested under a condition of submergence similar to that under which the model sills of this series were tested. However, sill B-12 was tested for a velocity of 0.77 foot per second in the flume, which corresponded to $4 \times 0.77 = 3.08$ feet per second in nature, whereas these later sills were tested for a velocity corresponding to 4 feet per second in nature. The observed backwater for B-12 was 0.0071 foot. As was observed in Paragraph 5, this appendix, the backwater effect varies as the square of the velocity, other conditions being unchanged. The computed backwater of sill B-12 for a velocity of 4 feet per second would then be $0.0071\ (4^2/3.08^2) = 0.0120$ foot, and the corresponding effect in nature would be $16 \times 0.0120 = 0.192$ foot. This value, obtained from data for a 1:16 model, checks the values obtained from the 1:60, 1:100, and 1:120 model sills.

TABLE 1, APPENDIX A

Backwater Effects of Individual Sills

Flume tests on 1:100 models of sills 12 feet high in channel 42 feet deep.

Type of Sill *	Upstream Face	Downstream Face	Model Data		Corresponding Natural Data	
			Velocity in Channel Approaching Sill *ft./sec.*	Observed Backwater Effect *ft.*	Velocity *ft./sec.*	Backwater Effect *ft.*
Type 1	1:1	1:1	0.400	0.0011	4.00	0.11
			0.573	0.0020	5.73	0.20
			0.695	0.0033	6.95	0.33
Type 2	5x5	5x5	0.400	0.0013	4.00	0.13
			0.573	0.0030	5.73	0.30
			0.695	0.0042	6.95	0.42
Type 3	1x6	1:1	0.400	0.0012	4.00	0.12
			0.573	0.0039	5.73	0.39
			0.695	0.0059	6.95	0.59
Type 4	Vertical	Vertical	0.400	0.0020	4.00	0.20
			0.573	0.0042	5.73	0.42
			0.695	0.0062	6.95	0.62

* For dimensions of sills, see Plate 11.

TABLE 2, APPENDIX A

Backwater Effects of Combinations of Sills

Flume tests on 1:100 models of sills 12 feet high in channel 42 feet deep.

Number of Sills	Model Data			Corresponding Natural Data	
	Velocity in Channel approaching Sill *ft./sec.*	Total Backwater Effect *ft.*	Backwater per Sill *ft.*	Velocity *ft./sec.*	Backwater per Sill *ft.*
Tests on sill 1 (both faces 1:1 slopes)—sills placed at intervals of 7 feet in the model flume.					
1	0.400	0.0010	0.0010	4.00	0.10
2	"	0.0028	0.0014	"	0.14
3	"	0.0033	0.0011	"	0.11
4	"	0.0040	0.0010	"	0.10
5	"	0.0055	0.0011	"	0.11
1	0.573	0.0020	0.0020	5.73	0.20
2	"	0.0040	0.0020	"	0.20
3	"	0.0070	0.0023	"	0.23
4	"	0.0090	0.0022	"	0.22
5	"	0.0101	0.0020	"	0.20
Tests on sill 4 (both faces vertical)—sills placed at intervals of 7 feet in the model flume.					
1	0.400	0.0020	0.0020	4.00	0.20
2	"	0.0041	0.0020	"	0.20
3	"	0.0061	0.0020	"	0.20
4	"	0.0079	0.0020	"	0.20
5	"	0.0096	0.0019	"	0.19
1	0.573	0.0047	0.0047	5.73	0.47
2	"	0.0097	0.0048	"	0.48
3	"	0.0131	0.0044	"	0.44
4	"	0.0176	0.0044	"	0.44
5	"	0.0220	0.0044	"	0.44
Tests on sill 4 (both faces vertical)—sills placed at intervals of 3½ feet in the model flume.					
1	0.400	0.0020	0.0020	4.00	0.20
2	"	0.0041	0.0020	"	0.20
3	"	0.0067	0.0022	"	0.22
4	"	0.0088	0.0022	"	0.22
5	"	0.0106	0.0021	"	0.21
6	"	0.0126	0.0021	"	0.21
7	"	0.0144	0.0021	"	0.21
8	"	0.0163	0.0020	"	0.20
9	"	0.0176	0.0020	"	0.20

TABLE 3, APPENDIX A

Backwater Effects of Model Sills Built to Different Scales

Flume tests on 1:60, 1:100, and 1:120 models of sills 12 feet high in channel 42 feet deep.

Number of Sills	Model Data			Corresponding Natural Data	
	Velocity in Channel approaching Sill *ft./sec.*	Total backwater Effect *ft.*	Backwater per Sill *ft.*	Velocity *ft./sec.*	Backwater per Sill *ft.*
Tests on 1:60 scale model sills, type 6* (both faces vertical), placed at intervals of 7 feet in the model flume.					
1	0.516	0.0033	0.0033	4.00	0.20
2	"	0.0061	0.0030	"	0.18
3	"	0.0084	0.0028	"	0.17
Tests on 1:100 scale model sills, type 4* (both faces vertical), placed at intervals of 7 feet in the model flume.					
1	0.400	0.0020	0.0020	4.00	0.20
2	"	0.0041	0.0020	"	0.20
3	"	0.0061	0.0020	"	0.20
Tests on 1:120 scale model sills, type 5* (both faces vertical), placed at intervals of 7 feet in the model flume.					
1	0.365	0.0014	0.0014	4.00	0.17
2	"	0.0027	0.0014	"	0.17
3	"	0.0047	0.0016	"	0.19

* For dimensions of sills, see Plate 11.

APPENDIX B

Computation of Effect of Sills

1. In a report entitled "Report of Proposed Compensation Works in St. Clair River", by Sherman Moore, Engineer, of the U. S. Lake Survey, the effect of the proposed submerged sills was computed by the following method:

> "12. *Methods of Computation*: In computing the effect of the contemplated submerged sills in the St. Clair River, the St. Lawrence Board assumed that the fall over each sill would be one-half of the difference in velocity head above and over the sill; in other words that there is a 50 per cent recovery of velocity head below this type of weir. In the present analysis the same assumption has been made. ---------------------It follows therefore that the amount of computed backwater rise to be effected by the sills is dependent almost wholly upon the assumption that one-half the head above each sill will be recovered below the sill. So far as is known there are no existing data to substantiate this assumption. --
>
> "21. As pointed out in Paragraph 12, the backwater resulting from the proposed sills is based almost wholly on an assumed recovery in velocity head of 50 per cent. It can be conceded that there will be some recovery and that the recovery will not be complete. If the recovery is 25 per cent, only two-thirds as many sills will be needed; if the recovery is 75 per cent, twice as many will be necessary.---------------"

Expressed as a formula, this method of computation may be written:

$$\text{Backwater effect} = \frac{K(V_1^2 - V_2^2)}{2g}, \text{ where}$$

V_1 = mean velocity of water flowing over the sill

V_2 = mean velocity of water in river channel approaching the sill, and

K = a coefficient.

For reasons stated in the above quotation, an arbitrary value of ½ was assigned to the coefficient K.

2. Since this method of computation had been used in planning the project, it was considered desirable to express the results of the flume and model tests made at the U. S. Waterways Experiment Station in terms of this backwater formula as an indication of how far its use might be justified. The values of the coefficient K that were computed from the results of the tests are listed in Tables 1, 2,

and 3, this appendix. In making this computation, the value of $\frac{(V_1^2 - V_2^2)}{2g}$ was first found for each sill. The observed backwater effect for any run divided by the summation of these values of $\frac{(V_1^2 - V_2^2)}{2g}$ for each sill used was taken then as the value of K. No "reflection" coefficient was introduced to express the relation between the backwater produced at the sites of the sills and that resulting in Lake Huron, as had been done in the computations for backwater effect in the report referred to at the beginning of the preceding paragraph. Such a coefficient would have had a value only slightly less than unity for these sills; its omission therefore has had little effect on the results.

3. The data in Tables 1, 2, and 3 indicate that the value of K has a somewhat definite relation to the shape of the sill, and that it varies considerably for different sill cross-sections. The values of K for the flume tests are rather consistently higher than the values for similar sills in the river model. This is presumably due to the difference between conditions of flow in the flume, where velocities were quite uniform in magnitude and direction over all the cross-section, and in the model, where velocities varied in both magnitude and direction, in accordance with those in the river. These irregularities in velocities and other factors were so pronounced in this problem, as in many others, that the reliable evaluation of the backwater effect did not appear to be possible without a river model study.

TABLE 1, APPENDIX B

Coefficients in St. Clair Sill Formula

Values computed from results of flume tests on individual sills.

Type of Sill		Reference			Model Scale	V_2 (Velocity in Channel without Sill) *ft./sec.*	$\frac{V_1^2-V_2^2}{2g}$	Observed Backwater	K
Upstream Face	Downstream Face	Type	Plate No.	Text					
Vertical	Vertical	B-12	I	Par. 19	1:16	0.780	0.0090	0.0071	0.79
"	"	B-7	I	"	1:16	0.780	0.0048	0.0026	0.54
"	"	6	II	App. A	1:60	0.516	0.0040	0.0028	0.70
"	"	4	II	"	1:100	0.400	0.0024	0.0020	0.83
"	"	4	II	"	1:100	0.573	0.0048	0.0042	0.88
"	"	4	II	"	1:100	0.695	0.0072	0.0062	0.86
"	"	5	II	"	1:120	0.365	0.0020	0.0016	0.80
"	1:3	C-12	I	Par. 19	1:16	0.780	0.0090	0.0072	0.80
"	1:3	C-7	I	"	1:16	0.780	0.0048	0.0037	0.77
6x1	1:1	3	II	App. A	1:100	0.400	0.0024	0.0012	0.50
6x1	1:1	3	II	"	1:100	0.573	0.0048	0.0039	0.81
6x1	1:1	3	II	"	1:100	0.695	0.0072	0.0059	0.82
1:1	Vertical	D-12	I	Par. 19	1:16	0.780	0.0090	0.0021	0.23
1:1	"	D-7	I	"	1:16	0.780	0.0048	0.0007	0.15
5x5	5x5	2	II	App. A	1:100	0.400	0.0024	0.0013	0.54
5x5	5x5	2	II	"	1:100	0.573	0.0048	0.0030	0.62
5x5	5x5	2	II	"	1:100	0.695	0.0072	0.0042	0.58
1:3	1:3	A-12	I	Par. 19	1:16	0.780	0.0090	0.0010	0.11
1:3	1:3	A-7	I	"	1:16	0.780	0.0048	0.0007	0.15
1:1	1:1	1	II	App. A	1:100	0.400	0.0024	0.0011	0.46
1:1	1:1	1	II	"	1:100	0.573	0.0048	0.0020	0.42
1:1	1:1	1	II	"	1:100	0.695	0.0072	0.0033	0.46

TABLE 2, APPENDIX B

Coefficients in St. Clair Sill Formula

Values computed from results of tests on distorted model.

Numbers of Sills in Model	Type of Sill		Value of Coefficient K		
	Upstream Face	Downstream Face	Q_n = 170,000 c. f. s.	Q_n = 194,000 c. f. s.	Q_n = 220,000 c. f. s.
1-8	Vertical	Vertical	0.51	0.55	0.56
1-8	1:3	1:3		0.15	
1-8	1:1	1:1		0.45	
2-7	Vertical	Vertical	0.59	0.58	
2-5, 7	"	"		0.56	0.61
2-5	"	"	0.50	0.61	0.62
2, 4, 6, 8	"	"		0.62	
2, 6-8	"	"		0.48	
1-8	Part Vert. " 1:3	Part Vert. " 1:3		0.31	
1-8	Part Vert. " 1:1	Part Vert. " 1:1		0.51	
1-8	Vertical	1:3		0.49	
1-8	1:3	Vertical		0.26	
1-8	Vertical	1:1		0.58	
1-8	1:1	Vertical		0.41	

TABLE 3, APPENDIX B

Coefficients in St. Clair Sill Formula

Values computed from results of tests on undistorted model.

Numbers of Sills in Model	Type of Sill		Value of Coefficient K		
	Upstream Face	Downstream Face	Q_n = 170,000 c. f. s.	Q_n = 194,000 c. f. s.	Q_n = 220,000 c. f. s.
1-8	Vertical	Vertical	0.62	0.59	0.62
1-8	"	1:1			0.60
1-8	"	1:3			0.63
1-8	1:1	1:1			0.50
1-8	1:3	1:3			0.28
1-8	1x5	1:1½			0.61
1-8	1x5	1:2	0.63	0.59	0.60
1-8	1x5	1:3	0.61	0.51	0.53
1-8	5x5	1:1½			0.48
1-8	5x5	1:2			0.48
1-8	{ 5x5 1:1 }	1:2			0.44
1-8, 7B	1:1	1:2			0.46
1-8, 7B	1x5	1:2	0.63	0.64	0.58
1-8, 7B	5x5	1:2	0.56	0.45	0.47
1-8, 7B	5x5	1:3			0.46
1-4, 5A, 5B, 6-8	1x5	1:2	0.61	0.60	0.59
1-4, 5A, 5B, 6-8	5x5	1:2	0.51	0.52	0.48
1, 2A, 2B, 3-8	5x5	1:2			0.40
1, 2A, 2B, 3-8	5x5	1:3			0.41
1, 2A, 2B, 3-8 7B	5x5	1:3			0.39

APPENDIX C

Summary of Data Observed in Experiments

1. These tables present in detail the essential parts of the experimental data observed in all the regular runs on the large indoor flume (Table 1) and on the distorted outdoor river model (Table 2). A tabulation of similar data for all the 595 runs on the undistorted river model is not included in this report, but data for typical runs for the various combinations tested are presented in Table 3.

TABLE 1, APPENDIX C

Summary of Backwater Data—Flume Tests

Model Scale – 1:16

Run No.	Sill Tested			Velocity at site of sill *ft./sec.*	Fall from Sta. +20 to Sta. —20 *ft.*	Backwater in Flume *ft.*
	Type	Upstream Face	Downstream Face			
1	None			0.774	0.0023	
2	A-12	1:3	1:3	1.087	0.0030	0.0007
3	A-12	1:3	1:3	1.092	0.0033	0.0012
4	None			0.772	0.0021	
5	"			0.774	0.0022	
6	D-12	1:3	Vertical	1.085	0.0043	0.0021
7	D-12	1:3	"	1.089	0.0039	0.0016
8	None			0.772	0.0023	
33	"			0.771	0.0015	
34	D-12	1:3	Vertical	1.078	0.0040	0.0025
9	None			0.773	0.0032	
10	C-12	Vertical	1:3	1.098	0.0095	0.0063
11	C-12	"	1:3	1.097	0.0100	0.0080
12	None			0.776	0.0020	
13	"			0.774	0.0024	
14	B-12	Vertical	Vertical	1.089	0.0092	0.0068
15	B-12	"	"	1.086	0.0092	0.0073
16	None			0.773	0.0019	
17	"			0.770	0.0015	
18	A-7	1:3	1:3	0.956	0.0023	0.0008
19	A-7	1:3	1:3	0.958	0.0025	0.0008
20	None			0.772	0.0017	
37	"			0.772	0.0014	
38	A-7	1:3	1:3	0.957	0.0023	0.0009
39	A-7	1:3	1:3	0.957	0.0028	0.0002
40	None			0.775	0.0026	
21	"			0.772	0.0024	
22	D-7	1:3	Vertical	0.959	0.0026	0.0002
23	D-7	1:3	"	0.958	0.0026	0.0007
24	None			0.773	0.0019	
35	"			0.772	0.0016	
36	D-7	1:3	Vertical	0.953	0.0027	0.0011
25	None	1:3		0.773	0.0018	
26	C-7	Vertical	1:3	0.962	0.0054	0.0036
27	C-7	"	1:3	0.958	0.0054	0.0037
28	None			0.772	0.0017	
29	"			0.773	0.0016	
30	B-7	Vertical	Vertical	0.951	0.0043	0.0027
31	B-7	"	"	0.951	0.0046	0.0025
32	None	"	"	0.967	0.0021	

TABLE 2, APPENDIX C

Summary of Backwater Data—Distorted Model.
Vertical scale 1:30; Horizontal scale 1:100

Run No.	Discharge in Model Q_m c. f. s.	Ratio, Model Q to Natural Q	Numbers of Sills in Model	Type of Sills: Upstream Face	Type of Sills: Downstream Face	Hook Gage Readings: Lake *ft.*	Hook Gage Readings: Black River *ft.*	Hook Gage Readings: Difference *ft.*	Backwater: From Runs	Backwater: Observed in Model *ft.*	Backwater: Corresponding in Nature *ft.*
					Natural Discharge (Q) = 194,000 c. f. s.						
11	13.4	1:14,500	0			1.5148	1.4736	0.0412			
16	13.4	1:14,500	0			1.5170	1.4755	0.0415			
22	13.5	1:14,400	0			1.5158	1.4744	0.0414			
27	13.4	1:14,500	0			1.5129	1.4731	0.0398			
43	13.6	1:14,300	0			1.5133	1.4729	0.0404			
49	13.5	1:14,400	0			1.5145	1.4755	0.0390			
54	13.6	1:14,300	0			1.5154	1.4773	0.0381			
55	13.6	1:14,300	0			1.5129	1.4741	0.0388			
61	13.6	1:14,300	0			1.5122	1.4731	0.0391			
12	13.5	1:14,400	1-8	Vertical	Vertical	1.5442	1.4761	0.0681	11, 12	0.0269	0.81
19	13.5	1:14,400	1-8	"	"	1.5396	1.4727	0.0669	16, 19	0.0254	0.76
44	13.6	1:14,300	1-8	"	"	1.5438	1.4775	0.0663	44, 49	0.0273	0.82
60	13.6	1:14,300	1-8	"	"	1.5384	1.4725	0.0659	55, 60	0.0271	0.81
13	13.5	1:14,400	1-8	1:3	1:3	1.5268	1.4790	0.0478	11, 13	0.0066	0.20
						1.5244	1.4780	0.0464		0.0052	0.16
45	13.5	1:14,400	1-8	1:3	1:3	1.5226	1.4749	0.0477	45, 49	0.0087	0.26
14	13.5	1:14,400	1-8	1:1	1:1	1.5368	1.4835	0.0533	11, 14	0.0121	0.36
						1.5373	1.4841	0.0532		0.0120	0.36
15	13.5	1:14,400	1-8	1:1	1:1	1.5317	1.4781	0.0536	11, 15	0.0124	0.37
50	13.5	1:14,400	1-8	1:1	1:1	1.5414	1.4814	0.0600	50, 54	0.0219	0.66
57	13.6	1:14,300	1-8	1:1	1:1	1.5317	1.4715	0.0602	55, 57	0.0214	0.64
53	13.6	1:14,300	1-8	Vertical	1:1	1.5473	1.4810	0.0663	53, 54	0.0282	0.85
56	13.6	1:14,300	1-8	"	"	1.5389	1.4724	0.0665	55, 56	0.0277	0.83
					Natural Discharge (Q_n) = 194,000 c. f. s.						
47	13.6	1:14,300	1-8	Vertical	1:3	1.5411	1.4784	0.0627	47, 49	0.0237	0.71
51	13.6	1:14,300	1-8	1:1	Vertical	1.5387	1.4807	0.0580	51, 54	0.0199	0.60
58	13.6	1:14,300	1-8	1:1	"	1.5283	1.4702	0.0581	55, 58	0.0193	0.58

TABLE 2, APPENDIX C—Continued.

Summary of Backwater Data—Distorted Model.

Vertical scale 1:30; Horizontal scale 1:100

Run No.	Discharge in Model Q_m c. f. s.	Ratio, Model Q to Natural Q	Numbers of Sills in Model	Type of Sills		Hook Gage Readings			Backwater		
				Upstream Face	Downstream Face	Lake *ft.*	Black River *ft.*	Difference *ft.*	From Runs	Observed in Model *ft.*	Corresponding in Nature *ft.*
				Natural Discharge (Q_n) = 194,000 c. f. s.—Continued.							
48	13.6	1:14,300	1-8	1:3	Vertical	1.5295	1.4783	0.0512	48, 49	0.0122	0.37
52	13.6	1:14,300	1-8	Part vert. " 1:1	Part vert. " 1:1	1.5418	1.4806	0.0612	52, 54	0.0231	0.69
59	13.6	1:14,300	1-8	Part vert. " 1:1	Part vert. " 1:1	1.5369	1.4726	0.0643	55, 59	0.0255	0.76
46	13.6	1:14,300	1-8	Part vert. " 1:3	Part vert. " 1:3	1.5313	1.4762	0.0551	46, 49	0.0151	0.45
17	13.5	1:14,400	2, 4, 6, 8	Vertical	Vertical	1.5356	1.4810	0.0546	16, 17	0.0131	0.39
18	13.5	1:14,400	2, 4, 6, 8	"	"	1.5300	1.4743	0.0557	16, 18	0.0142	0.43
21	13.5	1:14,400	2, 6, 7, 8	"	"	1.5252	1.4739	0.0513	16, 21	0.0098	0.29
29	13.4	1:14,500	2,3,4,5,7	"	"	1.5360	1.4770	0.0590	27, 29	0.0192	0.58
20	13.5	1:14,400	2, 3, 4, 5	"	"	1.5322	1.4736	0.0586	16, 20	0.0171	0.51
28	13.5	1:14,400	2-7	"	"	1.5376	1.4755	0.0621	27, 28	0.0223	0.67
62	13.6	1:14,300	1-8	"	"	1.5303	1.4762	0.0541	61, 62	0.0150	0.45
				Crests lowered 5 ft.							
				Natural Discharge (Q_n) = 220,000 c. f. s.							
30	14.5	1:15,200	0			1.5679	1.5248	0.0431			
34	14.5	1:15,200	0			1.5682	1.5257	0.0425			
38	14.6	1:15,100	0			1.5664	1.5260	0.0404			
42	14.6	1:15,100	0			1.5659	1.5251	0.0408			
31	14.5	1:15,200	1-8	Vertical	Vertical	1.5955	1.5276	0.0679	30, 31	0.0248	0.74
39	14.6	1:15,100	1-8	"	"	1.5943	1.5246	0.0697	38, 39	0.0293	0.88

TABLE 2, APPENDIX C—Continued.

Summary of Backwater Data—Distorted Model.

Vertical scale 1:30; Horizontal scale 1:100

Run No.	Discharge in Model Q_m c. f. s.	Ratio, Model Q to Natural Q	Numbers of Sills in Model	Type of Sills: Upstream Face	Type of Sills: Downstream Face	Hook Gage Readings: Lake ft.	Hook Gage Readings: Black River ft.	Hook Gage Readings: Difference ft.	Backwater: From Runs	Backwater: Observed in Model ft.	Backwater: Corresponding in Nature ft.
				Natural Discharge (Q_n) = 220,000 c. f. s.—Continued.							
33	14.5	1:15,200	2-5, 7	"	"	1.5878	1.5249	0.0629	30, 33	0.0198	0.59
40	14.6	1:15,100	2-5, 7	"	"	1.5884	1.5255	0.0629	38, 40	0.0225	0.68
32	14.5	1:15,200	2-5	"	"	1.5834	1.5245	0.0589	30, 32	0.0158	0.47
41	14.6	1:15,100	2-5	"	"	1.5847	1.5256	0.0591	38, 41	0.0187	0.56
				Natural Discharge (Q_n) = 170,000 c. f. s.							
23	11.0	1:15,500	0			1.4643	1.4336	0.0307			
26	10.9	1:15,600	0			1.4606	1.4337	0.0269			
35	10.9	1:15,600	0			1.4644	1.4353	0.0291			
24	10.9	1:15,600	1-8	Vertical	Vertical	1.4823	1.4346	0.0477	23, 24	0.0170	0.51
36	10.9	1:15,600	1-8	"	"	1.4849	1.4374	0.0475	35, 36	0.0184	0.55
25	10.9	1:15,600	2-5	"	"	1.4749	1.4343	0.0406	23, 25	0.0099	0.30
37	10.9	1:15,600	2-7	"	"	1.4809	1.4355	0.0454	35 37	0.0163	0.49

NOTES:

To convert the hook gage readings given in Table 2 to M. S. L. elevations, multiply the hook gage readings by 30, and add the product to 535.20. For example, in Run No. 11 the average reading of the Lake hook gage was 1.5148, so the corresponding M. S. L. elevation would be 1.5148 x 30 + 535.20 = 580.64.

In Runs Nos. 46, 52, and 59, the sills had vertical faces in the deep parts of the channel and sloping faces in the shallow parts. The deep sections of sills 1, 3, 4, and 5, on the Canadian side, were made with vertical faces, while the remaining sills and sections of sills were made with sloping faces as indicated in the table. In general, the sills had vertical faces when their height exceeded 18 feet.

In Run No. 62, the crests of all sills were made 5 feet (0.167 foot in the model) lower than the elevations given in Table 2 of the main report, which were used in all other tests.

TABLE 3, APPENDIX C

Summary of Backwater Data—Undistorted Model

Vertical scale 1:100; Horizontal scale 1:100

Numbers of Sills in Model	Type of Sills: Upstream Face	Type of Sills: Downstream Face	Hook Gage Readings: Lake Huron ft.	Hook Gage Readings: Mouth Black River ft.	Hook Gage Readings: Difference ft.	Backwater: Observed in Model ft.	Backwater: Corresponding in Nature ft.	Run No.
Natural Discharge (Q_n) = 220,000 c. f. s.								
0			1.8412	1.8285	0.0127			163N
1-8	Vertical	Vertical	1.8471	1.8285	0.0186	0.0059	0.59	164N
0			1.8426	1.8297	0.0129			172N
1-8	Vertical	1:1	1.8485	1.8298	0.0187	0.0058	0.58	173N
0			1.8402	1.8276	0.0126			181N
1-8	Vertical	1:3	1.8473	1.8285	0.0188	0.0062	0.62	179N 180N
0			1.8416	1.8286	0.0130			167N
1-8	1:1	1:1	1.8469	1.8290	0.0179	0.0049	0.49	168N
0			1.8414	1.8288	0.0126			176N
1-8	1:3	1:3	1.8437	1.8284	0.0153	0.0027	0.27	177N
0			1.8409	1.8277	0.0132			479N
1-8	1x5	1:1½	1.8470	1.8277	0.0193	0.0061	0.61	478N
0			1.8409	1.8278	0.0131			468N
1-8	1x5	1:2	1.8467	1.8277	0.0190	0.0059	0.59	469N
0			1.8410	1.8275	0.0135			401N
1-8	1x5	1:3	1.8466	1.8277	0.0189	0.0054	0.54	403N
0			1.8419	1.8292	0.0127			142N
1-8	1x5	1:1½	1.8459	1.8285	0.0174	0.0047	0.47	144N
0			1.8407	1.8278	0.0129			292N
1-8	5x5	1:2	1.8453	1.8275	0.0178	0.0049	0.49	293N
0			1.8408	1.8282	0.0126			192N
1-8	5x5, 1:1	1:2	1.8441	1.8272	0.0169	0.0043	0.43	195N
0			1.8408	1.8282	0.0126			228N
1-8, 7B	1:1	1:2	1.8455	1.8280	0.0175	0.0049	0.49	227N
0			1.8405	1.8275	0.0130			451N
1-8, 7B	1x5	1:2	1.8465	1.8273	0.0192	0.0062	0.62	452N
0			1.8410	1.8280	0.0130			204N
1-8, 7B	5x5	1:2	1.8463	1.8282	0.0181	0.0051	0.51	207N
0			1.8408	1.8282	0.0126			228N
1-8, 7B	5x5	1:3	1.8460	1.8285	0.0175	0.0049	0.49	229N
0			1.8409	1.8275	0.0134			443N
1-4, 5A 5B, 6-8	1x5	1:2	1.8477	1.8277	0.0200	0.0066	0.66	444N
0			1.8400	1.8265	0.0135			319N
1-4, 5A, 5B, 6-8	5x5	1:2	1.8450	1.8260	0.0190	0.0055	0.55	317N

TABLE 3, APPENDIX C—Continued.

Summary of Backwater Data—Undistorted Model

Vertical scale 1:100; Horizontal scale 1:100

Numbers of Sills in Model	Type of Sills		Hook Gage Readings			Backwater		Run No.
	Up-stream Face	Down-stream Face	Lake Huron *ft.*	Mouth Black River *ft.*	Difference *ft.*	Observed in Model *ft.*	Corresponding in Nature *ft.*	
Natural Discharge (Q_n) = 220,000 c. f. s.—Continued.								
0			1.8408	1.8282	0.0126			210N
1, 2A, 2B, 3-8	5x5	1:2	1.8452	1.8277	0.0175	0.0049	0.49	212N
0			1.8419	1.8292	0.0127			233N
1, 2A, 2B, 3-8	5x5	1:3	1.8465	1.8286	0.0179	0.0052	0.52	234N
0			1.8410	1.8280	0.0130			237N
1, 2A, 2B, 3-8, 7B	5x5	1:3	1.8460	1.8280	0.0180	0.0050	0.50	236N
Natural Discharge (Q_n) = 194,000 c. f. s.								
0			1.8240	1.8125	0.0115			492N
1-8	Vertical	Vertical	1.8291	1.8126	0.0165	0.0050	0.50	493N
0			1.8245	1.8133	0.0112			429N
1-8	1x5	1:2	1.8306	1.8140	0.0166	0.0054	0.54	430N
0			1.8238	1.8123	0.0115			239N
1-8	1x5	1:3	1.8280	1.8120	0.0160	0.0045	0.45	240N
0			1.8239	1.8124	0.0115			355N
1-8, 7B	1x5	1:2	1.8303	1.8126	0.0177	0.0062	0.62	358N
0			1.8243	1.8125	0.0118			384N
1-8, 7B	5x5	1:2	1.8290	1.8128	0.0161	0.0043	0.43	386N
0			1.8248	1.8134	0.0114			438N
1-4, 5A, 5B, 6-8	1x5	1:2	1.8310	1.8136	0.0174	0.0060	0.60	439N
0			1.8243	1.8125	0.0118			384N
1-4, 5A, 5B, 6-8	5x5	1:2	1.8300	1.8132	0.0168	0.0050	0.50	387N
Natural Discharge (Q_n) = 170,000 c. f. s.								
0			1.8115	1.8020	0.0095			503N
1-8	Vertical	Vertical	1.8160	1.8020	0.0140	0.0045	0.45	504N
0			1.8101	1.8006	0.0095			457N
1-8	1x5	1:2	1.8158	1.8014	0.0144	0.0049	0.49	458N
0			1.8100	1.8005	0.0095			258N
1-8	1x5	1:3	1.8145	1.8004	0.0141	0.0046	0.46	256N
0			1.8113	1.8015	0.0098			376N
1-8, 7B	1x5	1:2	1.8165	1.8015	0.0150	0.0052	0.52	372N

TABLE 3, APPENDIX C—Continued.

Summary of Backwater Data—Undistorted Model

Vertical scale 1:100; Horizontal scale 1:100

Numbers of Sills in Model	Type of Sills		Hook Gage Readings			Backwater		Run No.
	Up-stream Face	Down-stream Face	Lake Huron *ft.*	Mouth Black River *ft.*	Difference *ft.*	Observed in Model *ft.*	Corresponding in Nature *ft.*	
Natural Discharge $Q_n = 170{,}000$ c. f. s.—Continued.								
0			1.8100	1.8003	0.0097			377N
1-8, 7B	5x5	1:2	1.8153	1.8010	0.0143	0.0046	0.46	378N
0			1.8109	1.8013	0.0096			333N
1-4, 5A, 5B, 6-8	1x5	1:2	1.8173	1.8022	0.0151	0.0055	0.55	335N
0			1.8100	1.8003	0.0097			377N
1-4, 5A, 5B, 6-8	5x5	1:2	1.8151	1.8010	0.0141	0.0044	0.44	380N

NOTE:—To convert model gage readings to M. S. L elevations, add 3.981 to the gage reading and multiply the sum by 100. For example, in Run No. 380N the average reading of the Lake Hook gage was 1.8151, so the corresponding M. S. L. elevation would be 100 x (1.8151 + 3.981) = 579.61 feet.

APPENDIX D

COMPARISON OF RESULTS FROM THE DISTORTED AND UNDISTORTED MODELS

Synopsis

1. After the completion of the tests on which the foregoing sections of this report are based, further special tests were made on the existing undistorted model, so that the results might be compared more directly with those indicated by the earlier distorted model. When operating conditions for the undistorted model were made as nearly as possible the same as those that had existed for the distorted model, it was found that:

(a) For sills with both faces vertical, the backwater effects indicated by the two models were sensibly the same.

(b) For sills with 1:1 slopes on both upstream and downstream faces, the backwater effects were also the same.

(c) For sills with 1:3 slopes on both faces, the backwater indicated by the undistorted model was about twice that for the distorted model.

Conditions for Tests on Distorted Model

2. The procedure followed in making tests on the distorted model is described in Paragraph 27 of the body of this report. Briefly, this procedure was as follows: After the model channel had been roughened as much as appeared practicable, the model discharge was adjusted until the natural water-surface profile was properly simulated. Backwater effects were found by comparing runs made with and without sills. The model discharges used exceeded the theoretical values by 5%, 14%, and 9% for natural discharges of 170,000, 194,000, and 220,000 c. f. s., respectively.

Conditions for Regular Tests on Undistorted Model

3. The procedure followed in making regular tests on the undistorted model is described in Paragraph 35 of the body of this report. In these tests the model discharge was first set at the value indicated by the theory of similitude ($Q_m = Q_n l d^{3/2} = Q_n l^{5/2}$). The water-surface elevations at the upper and lower gages were then adjusted to the proper values by a slight alteration of the roughness of the model channel. For most of the runs the sills used in this model were in the same locations as those in the distorted model,

but the elevations of the sill crests were made slightly lower, following the receipt of later information from the Detroit Office of the U. S. Lake Survey.

Conditions for Comparison Tests on the Undistorted Model

4. These special tests were made under conditions similar to those that had existed for the distorted model. The model discharges were increased over the theoretical values by the same percentages that had previously been used in the distorted model, and the sill crests were raised to the same elevations as those used in the distorted model.

Results

5. Table 1 shows a comparison of the backwater effects obtained from the two models with the crests of the sills at the same elevations and with the discharge of the undistorted model the same percentage of the theoretical discharge (as given by the expression $q = ld^{3/2}$) as had been used in the distorted model.

6. Table 2 shows the backwater effects indicated by the undistorted model when operated under three different sets of conditions. The regular tests (Series A) were made under the conditions described in Paragraph 3 of this appendix, with the sill crests at the elevations ordinarily used for this model, and with the model discharges maintained at the theoretical values. For the tests of Series B, the same theoretical discharges were used, but the sill crests were raised to the elevations used in the distorted model. For the tests of Series C, the discharges were increased over the theoretical values by the same percentage as had previously been used in the distorted model for a natural discharge of 194,000 c. f. s., while the crests of the sills were kept at the same elevations as for the tests of Series B.

Comparison of Results

7. There is considerable difference between the results from the distorted model and those obtained from the regular runs on the undistorted model, as can be seen by a comparison of the data for the distorted model in Table 1 with the data of Series A in Table 2.

8. However, when the sills of the undistorted model were raised to the same elevations as those that had been used in the distorted model, and when the discharges of the undistorted model were increased over the theoretically required values by the same percentages that had been used in the distorted model, the results generally agreed quite closely, as can be seen in Table 1. These tests on the undistorted model indicated that, at least for sills vertical or 1:1 sloping faces, the two models would have shown approximately the same backwater effects, if a better adjustment of the distorted model had been obtained so that the discharge scale used could have

been according to Froudian relationships, and if sills with the same crest elevations had been tested.

9. The results (as shown in Table 1) of the special tests on the undistorted model for the 1:1 sloping face sills indicate close agreement of the backwater effects obtained from the undistorted and distorted models. This close agreement is not indicated by the special tests on the 1:3 sloping face sills. Since it was immediately apparent that sills with wide slopes of 1:3 were the least efficient of any of those tested, the results obtained from the distorted model for these sills were not as thoroughly checked as the other data. It is possible that a closer agreement between the two models would have been obtained had more complete tests for the 1:3 sills been made on the distorted model.

10. The difference in backwater effects indicated by tests on the same model with sills of two different crest elevations may be seen by comparing the data of Series A and B of Table 2. The difference caused by increasing the model discharge may be seen by comparing Series B and C of Table 2.

TABLE 1, APPENDIX D

Comparison of Backwater Effects from Distorted and Undistorted Models

Backwater effects of Sills 1-8. Crests of sills in undistorted model at same elevation as those previously tested in distorted model. Discharge of undistorted model exceeded the theoretical discharge by the same percentage that had previously been used in the distorted model.

Model	Type of Sill		Natural Discharge c. f. s.	Ratio, Actual Q_m to Theoretical Q_m.	Observed Backwater Effect (Feet in Nature)
	Upstream Face	Downstream Face			
Distorted	Vertical	Vertical	170,000	1.05	0.53
Undistorted	"	"	170,000	1.05	0.60
Distorted	"	"	194,000	1.14	0.80
Undistorted	"	"	194,000	1.14	0.76
Distorted	"	"	220,000	1.09	0.81
Undistorted	"	"	220,000	1.09	0.78
Distorted	1:1*	1:1	194,000	1.14	0.65
Undistorted	1:1	1:1	194,000	1.14	0.69
Distorted	1:3	1:3	194,000	1.14	0.21
Undistorted	1:3	1:3	194,000	1.14	0.44

* These are actual slopes in the model and have not, in the distorted model, been distorted according to the scales of the model.

TABLE 2, APPENDIX D

Backwater Effects from Undistorted Model, for Different Conditions

All these data are from tests on sills 1-8, with both faces vertical. Elevations of crests of sills were either "high", as used for the regular runs on the distorted model (see Table 2 of main report); or "low", as used for the regular runs on the undistorted model (see Table 4 of main report).

Series	Sill Crests	Natural Discharge c. f. s.	Ratio, Actual Q_m to Theoretical Q_m	Observed Backwater Effect (Feet in Nature)
A	"low"	170,000	1.00	0.47
A	"	194,000	1.00	0.52
A	"	220,000	1.00	0.61
B	"high"	170,000	1.00	0.52
B	"	194,000	1.00	0.63
B	"	220,000	1.00	0.69
C	"high"	170,000	1.14	0.65
C	"	194,000	1.14	0.76
C	"	220,000	1.14	0.92

APPENDIX E

REPORT ON TESTS OF BACKWATER RESULTING FROM DEEPLY SUBMERGED WEIRS MADE BY THE U. S. LAKE SURVEY IN THE HYDRAULIC LABORATORY OF THE UNIVERSITY OF MICHIGAN JANUARY-FEBRUARY, 1932

1. Under authority from the Chief of Engineers, (2d Ind. 7432 (Great Lakes)-109), and after submitting the proposed program to the officer in charge of the U. S. Waterways Experiment Station at Vicksburg, Miss., a series of tests to determine the backwater resulting from deeply submerged weirs was made in the Hydraulic Laboratory of the University of Michigan in January and February, 1932. The program for the tests was planned by the late F. G. Ray, Principal Engineer, and the work was done under his supervision by Lake Survey personnel, with assistance from personnel of the University. The computations involved and the analysis of results were made by Sherman Moore, Engineer. Valuable advice and suggestions were contributed by Professors King and Wisler of the University Staff.

2. Plate 12, accompanying this report, shows diagramatically the apparatus in the Hydraulic Laboratory that was used in the experiments. From a supply pit below the first floor of the Engineering Building, an electrically driven 16-inch centrifugal pump delivered water through a 15-inch supply pipe to a steel stilling tank on the third floor of the building. Control of the quantity delivered was regulated in part by rheostat control on the motor and in part by a gate valve near the end of the supply pipe. From one corner of this tank, through screens and a cellular baffle, the water entered a timber flume 2 feet wide, 4 feet deep, and 47 feet long. At the lower end of the flume, angle irons projecting about 1-¼ inches from the sides and bottom held the boards used in baffling the flow. From the flume the water passed through a metal conduit to a receiving tank, and thence over a 90-degree V-notch weir back to the supply pit. The pump could supply a steady flow of 11 c. f. s. The constriction in cross-section at the lower end of the flume limited the maximum velocity to slightly more than 3 feet per second.

3. The head on the V-notch weir, which was used to determine the volume of flow through the flume, was read by a hook gage in a stilling box. This weir was not calibrated anew, but the zero reading of the hook gage was determined at intervals. The equation used for flow over the weir, $Q = 2.505 H^{2.48}$, is the result of several calibrations, by personnel of the Hydraulic Department of the University, and is believed to be more accurate than any determination which could have been made by the Lake Survey in the time available.

4. For measuring water levels in the flume three point gages were installed on the center line of the flume. The upper gage was 16 feet from the supply tank, the intermediate gage 10 feet below the upper, and the lower gage was 14 feet below the intermediate gage and 7 feet from the end of the flume. All models were placed in the flume with the lower edge of the crest directly under the intermediate gage. The zero of the upper gage was at the mean bottom

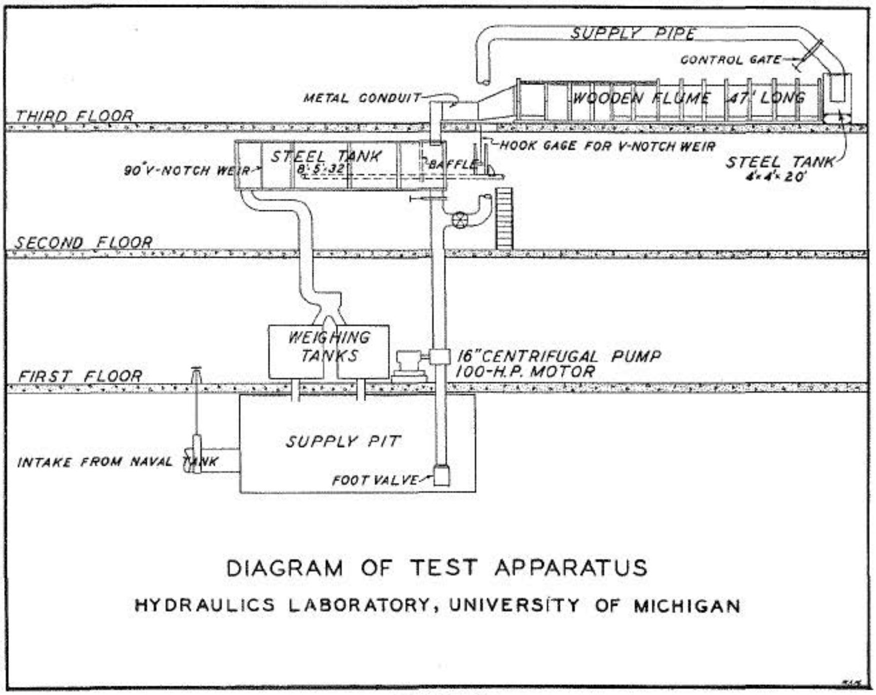


PLATE 12

of the flume, which was practically level. The zero readings of the intermediate and the lower gages were referred to that of the upper gage through simultaneous observations of the three gages on a still water surface. It was found that these zero readings did not remain constant but varied with the amount of water in the flume, and changed slightly from day to day. As these corrections, which were small and probably due to flexure of the flume and the floor, were determined at frequent intervals, it is believed that no appreciable error enters from this cause.

5. The mean width of the flume between the upper and the lower gates was determined at 2-foot intervals in length and 0.34-foot intervals, or the width of a plank, in height. The sides sloped slightly inward, the mean width at the bottom being 2.03 feet and the top 2.01 feet.

6. Under ordinary conditions the point gages could be read with considerable accuracy, but with velocities of 3 feet per second waves traveling down the flume gave some trouble. At this velocity with some models in the flume, readings at the intermediate gage became very uncertain, and readings of the lower gage were apparently affected by waves. None of these conditions existed with current velocities less than 2 feet per second. To eliminate personal equation, a system of 12 readings for each test run was adopted, in which by the interchange of observers this error was eliminated from each group of 6 readings. Forty-five observations under varying conditions of flow were made to determine the normal fall in the flume. The scattering of the observations at the higher current velocities, although not great, was sufficient to prevent the determination of a friction equation. It was decided to adopt the Manning formula $v = \frac{1.486}{n} R^{2/3}S^{1/2}$, and to utilize the observations to determine the value of n. The value determined from the observations was 0.0107. With this value of n, the following equations give the normal fall in the flume.

$$\text{Upper End} \quad F = 0.000525 \frac{V^2}{R^{4/3}}$$

$$\text{Lower End} \quad F = 0.000736 \frac{V^2}{R^{4/3}}$$

7. The backwater experiments fall into several groups. In series A, B, C, and S, no attempt was made to apply Froudian relationships. These tests were planned to show the relation between backwater and change in velocity head, if such relation existed, with velocities approximating those in the river, and with backwater effects large enough to be easily measured. The models were built of planed lumber, with 6-inch horizontal crests, slopes above and below of 1:3, and heights of 2⅜, 3⅞, 5¼, and 7 inches. In series A the depths over and below the weir were held constant by baffling and by varying the flow in the flume. In Series B the flow was held at approximately 11 c. f. s. and the velocity was varied from 2 to 3 feet per second by baffling to different depths. In Series S, the 7-inch model only was used, and the flow varied from 1½ to 11 c. f. s. with no baffling. This series was run in order that the tests might overlap, in percentage submergence, other experiments on submerged weirs. Series C was made to determine the effect of varying the downstream slope of the weir. The 5¼-inch model was used first with vertical downstream face, then with downstream slope of 1½ to 1.

8. In Series D and E, the models were built to a scale of 1:16, and observations were made with similitude velocities and depths. Additional observations were made at higher velocities to correlate these Series with Series A, B, C, and S. In Series E three models were used, built up in the flume with crushed stone, proportional in size to that which would be used in the river. Two models had crest widths of about 37 inches, slopes of 1:3, and heights of 5¼ and 10 inches, duplicating the sills proposed by the St. Lawrence Board on a scale of 1:16. The lower model approximated the average con-

dition obtaining at the proposed sill sites; the higher model corresponded to conditions at the most effective site. The third model consisted of irregular mounds of stone.

9. The results obtained from Series A and B, checked by those from Series E, having indicated that the effect of the proposed sills had been greatly overestimated, some experiments were made on other methods of contraction. Series D shows the effect of rows of piles driven into the bed of the stream with their tops 30 feet below the surface. Two models were used, both to a similitude scale of 1:16. Wooden cylinders ⅞-inch in diameter, 4⅞ inches high, were fastened to metal plates, ⅜-inch thick and 4 inches wide, with beveled edges. In one model the cylinders were placed in a single row, 1¼ inches center to center. In the other model, three rows 1 inch apart center to center were used, the cylinders being spaced 1¾ inches center to center, those of the middle row with their centers halfway between the centers of the cylinders in the two outside rows.

10. The experiments of Series F were planned to determine the backwater resulting from a row of sheet piling across the bottom. In F-1 and F-2 a strip of galvanized iron 4⅞ inches wide was placed on the upper side of the 3-row pile model. In F-4 and F-5, a ¾-inch board beveled at the top was placed across the flume, in F-5 the upstream side being built up to a 1:3 slope with crushed stone. In F-3 the metal strip was placed on the upstream side of the single-row pile model, and the upstream side was built up to a 1:3 slope with crushed stone. While the models are not strictly comparable, the effect of the piles below the plate appears to be inappreciable.

11. The results of the experimental tests are shown in detail in Table 2, accompanying this report. The area over the weir in each case is determined from the reading of the intermediate gage. This is not the minimum area with models of 1:3 downstream slope, the minimum area with such models occurring below the gage on the apron. The percentage obstruction is the height of the weir divided by the depth at the lower gage. Normal falls are computed by means of the equations in Paragraph 6, and represent the frictional losses in the flume exclusive of those caused by the weir.

12. After considerable study, it was decided that the experiments in themselves were insufficient for the derivation of a rational formula for deeply submerged weirs. They seem to show that none of the existing formulas are correct when the percentage submergence, that is, the ratio of the head below the weir divided by the head above the weir, exceeds 90 per cent. They also show that the recovery of velocity head below the weir varies both with the velocity and with the percentage obstruction.

13. Assuming that the backwater (F) must vary as the square of the velocity (V), and as some function of the percentage obstruction, which in the experiments is the height of the weir (W) divided by the depth in the flume (D), best results were obtained by plotting $\frac{F}{V^2}$ against $\frac{W}{D}$. The backwater appears to be an exponential function of $\frac{W}{D}$, the exponent depending upon the shape of the weir. For 1:3 slopes on both upstream and downstream sides, F varies as

$(W/D)^4$; with vertical downstream side, F varies as $(W/D)^{2.4}$, irrespective of the upstream slope. Observations on the stone weirs of Series E fail to follow this law, or any other thus far discovered. If the observations with velocities exceeding 2 feet per second are omitted, the factor $(W/D)^4$ seems to fit fairly well, although the residuals are larger than in other models. Some other factor, probably the width of the crest, seems to be present.

14. With the pile models, F appears to vary as $(W/D)^{2.2}$ when W is taken as the height of the top of the piles. For the model with three rows of piles, the four observations, with velocities ranging from 0.8 to 3.0 feet per second show a maximum residual of 0.0004 foot. With the single row the observations plot well except the one at 3 feet per second which shows a residual of 100 per cent. This observation appeared erroneous at the time, and was repeated with no material change in the result.

15. Similitude tests of Series D, E, and F were based on the following conditions, which agree approximately with the mean conditions at the sites of the proposed sills in the St. Clair River: Velocity 3.76 feet per second, mean depth 37.00 feet, height of sill 7.00 feet. In Table 1 the backwater corresponding to this condition has been computed by means of the relation $F = KV^2(W/D)^n$, and compared with the backwater observed in the similitude tests multiplied by the scale ratio of 16. The comparison shows that the results by the similitude tests and those derived by formulas are in substantial agreement. The discrepancies are largely due to departure of the scale tests from the assumed conditions. The stone models settled to some extent after they became wet, and it was impracticable to secure exact depths and velocities without undue loss of time. Unavoidable errors in the gage readings have been multiplied by 16.

TABLE 1, APPENDIX E

Comparison of Backwater Effects

Character of Obstruction	Backwater, in Feet	
	By Equation	By Similitude Test
Sills proposed by the Board	0.015	0.012
One row of piling	0.054	0.044
Three rows of piling	0.040	0.041
Sheet piling or cribwork	0.094	0.091
Sheet piling or cribs, with fill above	0.036	0.026

16. The St. Lawrence Board proposed to raise Lake Huron 0.85 foot by 31 sills in the St. Clair River, at a cost of $2,700,000. Revised computations made by the Lake Survey in 1931 showed that

the necessary compensation to be secured in the St. Clair River, with a diversion of 3,200 c. f. s. at Chicago, is 0.54 foot, and that such compensation could be secured by 11 sills at an estimated cost of $820,000. Both of these computations are based on the assumption that 50 per cent of the velocity head created by the sills would be recovered. For the mean conditions used in computing the table above, this assumption shows a backwater rise of 0.054 foot for each sill. The table shows that the backwater resulting from a sill of the type proposed by the Board would be about one-fourth of that estimated, and that more than 40 sills of this type would be required to secure a backwater rise of 0.54 foot on Lake Huron, at a cost in excess of $3,000,000.

17. If it were possible to drive rows of piles across the river with their tops 30 feet below the surface, compensation could be secured with 12 such rows. The cost of driving the piles can not be estimated readily, as special equipment for driving them would be necessary. There is some doubt as to whether piles projecting more than 30 feet above the bottom could be held in place.

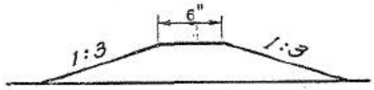
18. The backwater resulting from a row of sheet piling makes some such scheme attractive. Sheet piling would be difficult to drive, and it might be impracticable to hold in place. It is believed that substantially the same backwater would result from rock-filled cribs placed end to end across the river. Only six rows would be needed, provided there was no deposition of silt above them. It is not known how much material could be deposited above the sills without seriously affecting their efficiency, but should the fill reach the top of the sill, the loss would approximate 60 per cent. The St. Clair River carries very little material in suspension, and it may be that dredging at infrequent intervals would maintain the efficiency of the sills at small expense. If cribs were used, openings near the river bottom would prevent much silting above them, and might increase their efficiency. Construction of six such sills near the head of the river would require about 5,000 feet of crib work averaging 12 feet in height. Assuming a cost of $100 per lineal foot, which seems conservative, the total cost would amount to $500,000.

19. It is believed that these experiments have served the primary purpose for which they were planned. They seem to show conclusively that the assumption upon which calculations have been based, that one-half of the energy required to pass a deeply submerged sill is lost, is not well founded. The loss of energy in passing such an obstruction seems to depend very largely upon the amount of turbulence produced. If it appears desirable or necessary to hold to the general scheme as proposed by the St. Lawrence Board, which has Congressional approval, of compensating for lowered levels in Lake Huron by obstructions placed below the thirty-foot depth in the St. Clair River, it would seem desirable to determine by further experiments the most economical form for such obstruction. Facilities at the Hydraulic Laboratory of the University of Michigan are inadequate for such experiments.

TABLE 2, APPENDIX E

Observed Data of Experiments in Hydraulics Laboratory, University of Michigan, 1932.

PLAIN MODELS



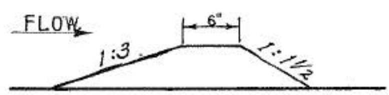
Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
A-1	Feb. 3	Upper	2.1357		4.310		2.555		0.0056	
		Inter.	2.0019	0.6023	2.813	28.6	3.914		0.0084	
		Lower	2.0943		4.224		2.607	0.0414	0.0140	0.0274
A-2	Feb. 3	Upper	2.1012		4.236		2.175		0.0041	
		Inter.	2.0163	0.6023	2.844	28.9	3.235		0.0060	
		Lower	2.0779		4.190		2.198	0.0233	0.0101	0.0132
A-3	Feb. 3	Upper	2.0543		4.143		1.909		0.0032	
		Inter.	1.9920	0.6023	2.796	29.5	2.829		0.0046	
		Lower	2.0356		4.107		1.926	0.0187	0.0078	0.0109
A-4	Jan. 27	Upper	1.6773		3.387		2.610		0.0066	
		Inter.	1.6310	0.2223	2.846	13.4	3.106		0.0097	
		Lower	1.6523		3.335		2.652	0.0250	0.0163	0.0087
A-5	Jan. 27	Upper	1.6797		3.390		2.401		0.0056	
		Inter.	1.6424	0.2223	2.865	13.3	2.841		0.0082	
		Lower	1.6579		3.348		2.431	0.0218	0.0138	0.0080
A-6	Jan. 26	Upper	1.6282		3.287		1.981		0.0039	
		Inter.	1.6085	0.2223	2.796	13.7	2.328		0.0055	
		Lower	1.6166		3.265		1.994	0.0116	0.0094	0.0022
B-7	Feb. 3	Upper	2.7668		5.573		1.967		0.0031	
		Inter.	2.7325	0.6023	4.282	21.8	2.560		0.0043	
		Lower	2.7534		5.546		1.976	0.0134	0.0074	0.0060
B-8	Feb. 3	Upper	2.2461		4.531		2.432		0.0051	
		Inter.	2.1467	0.6023	3.110	27.0	3.543		0.0073	
		Lower	2.2190		4.473		2.464	0.0271	0.0124	0.0147
B-9	Feb. 3	Upper	1.9010		3.838		2.858		0.0075	
		Inter.	1.6415	0.6023	2.093	33.1	5.241		0.0119	
		Lower	1.8087		3.648		3.007	0.0923	0.0194	0.0729
B-10	Jan. 29	Upper	2.7643		5.569		1.955		0.0030	
		Inter.	2.7426	0.4538	4.603	16.4	2.366		0.0043	
		Lower	2.7547		5.550		1.962	0.0096	0.0073	0.0023
B-10	Jan. 29	Upper	2.7634		5.567		1.974		0.0031	
		Inter.	2.7441	0.4538	4.600	16.4	2.389		0.0043	
		Lower	2.7544		5.548		1.981	0.0090	0.0074	0.0016
B-11	Jan. 30	Upper	2.2233		4.483		2.463		0.0052	
		Inter.	2.1708	0.4538	3.455	20.4	3.195		0.0074	
		Lower	2.2068		4.451		2.480	0.0165	0.0126	0.0039

TABLE 2, APPENDIX E—Continued.

Observed Data of Experiments in Hydraulics Laboratory, University of Michigan, 1932.

Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
B-12	Jan. 30	Upper	1.9964		4.028		2.743		0.0068	
		Inter.	1.8792	0.4538	2.868	22.9	3.853		0.0098	
		Lower	1.9684		3.973		2.781	0.0280	0.0166	0.0114
B-13	Feb. 5	Upper	2.7638		5.563		1.967		0.0031	
		Inter.	2.7521	0.3318	4.868	12.1	2.247		0.0043	
		Lower	2.7559		5.552		1.970	0.0079	0.0074	0.0005
B-14	Jan 28	Upper	2.2340		4.505		2.440		0.0051	
		Inter.	2.2002	0.3318	3.762	15.0	2.921		0.0073	
		Lower	2.2198		4.477		2.455	0.0142	0.0124	0.0018
B-15	Jan. 28	Upper	1.8371		3.708		2.956		0.0081	
		Inter.	1.7483	0.3318	2.854	18.2	3.840		0.0119	
		Lower	1.8109		3.656		2.998	0.0262	0.0200	0.0062
B-16	Jan. 27	Upper	2.7453		5.529		1.995		0.0031	
		Inter.	2.7347	0.2223	5.058	8.1	2.181		0.0045	
		Lower	2.7355		5.510		2.002	0.0098	0.0076	0.0022
B-17	Jan. 27	Upper	2.2077		4.453		2.459		0.0052	
		Inter.	2.1862	0.2223	3.958	10.1	2.767		0.0074	
		Lower	2.1921		4.420		2.477	0.0156	0.0126	0.0030
B-18	Jan. 27	Upper	1.8510		3.737		2.946		0.0081	
		Inter.	1.7981	0.2223	3.177	12.1	3.466		0.0116	
		Lower	1.8296		3.694		2.980	0.0214	0.0197	0.0017
S-1	Feb. 3	Upper	1.7140		3.458		2.611		0.0066	
		Inter.	1.4269	0.6023	1.660	37.5	5.440		0.0111	
		Lower	1.5937		3.216		2.808	0.1203	0.0177	0.1026
S-2	Feb. 2	Upper	1.5396		3.109		2.248		0.0052	
		Inter.	1.2623	0.6023	1.328	43.3	5.264		0.0095	
		Lower	1.3805		2.787		2.508	0.1591	0.0147	0.1444
S-3	Feb. 2	Upper	1.3642		2.755		1.837		0.0037	
		Inter.	1.0993	0.6023	0.998	51.8	5.070		0.0080	
		Lower	1.1536		2.330		2.172	0.2106	0.0117	0.1989
S-4	Feb. 2	Upper	1.1597		2.342		1.281		0.0020	
		Inter.	0.9343	0.6023	0.668	66.9	4.491		0.0055	
		Lower	0.8952		1.808		1.659	0.2645	0.0075	0.2570

PLAIN MODELS, SLOPE VARIATIONS



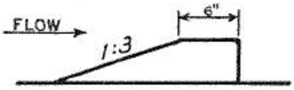
C-1	Feb. 1	Upper	2.7628		5.563		1.979		0.0031	
		Inter.	2.7395	0.4508	4.599	16.3	2.394		0.0044	
		Lower	2.7529		5.543		1.986	0.0099	0.0075	0.0024

TABLE 2, APPENDIX E—Continued.

Observed Data of Experiments in Hydraulics Laboratory, University of Michigan, 1932.

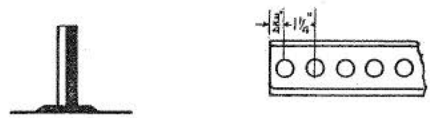
Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
C-2	Feb. 1	Upper	1.8411		3.718		2.953		0.0081	
		Inter.	1.6839	0.4508	2.482	24.8	4.424		0.0120	
		Lower	1.8029		3.638		3.018	0.0382	0.0201	0.0181

PLAIN MODELS, SLOPE VARIATIONS



Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
C-3	Jan. 30	Upper	2.7674		5.574		1.963		0.0031	
		Inter.	2.7411	0.4508	4.603	16.4	2.377		0.0043	
		Lower	2.7549		5.548		1.972	0.0125	0.0074	0.0051
C-4	Feb. 1	Upper	1.8387		3.710		2.968		0.0082	
		Inter.	1.6811	0.4508	2.474	25.4	4.450		0.0127	
		Lower	1.7671		3.567		3.087	0.0716	0.0209	0.0507

PILE MODEL, SINGLE ROW

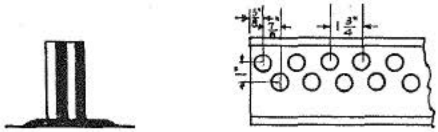


Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
D-1	Feb. 8	Upper	1.8439		3.723		2.938		0.0080	
		Inter.	1.7908	0.442	2.995	17.4	3.653		0.0121	
		Lower	1.7966		3.626		3.017	0.0473	0.0201	0.0272
D-1	Feb. 15	Upper	1.8411		3.719		2.950		0.0081	
		Inter.	1.7863	0.442	2.986	17.4	3.674		0.0122	
		Lower	1.7904		3.614		3.035	0.0507	0.0203	0.0304
D-2	Feb. 8	Upper	2.2501		4.540		2.423		0.0050	
		Inter.	2.2197	0.442	3.857	13.6	2.852		0.0073	
		Lower	2.2118		4.462		2.465	0.0383	0.0123	0.0260
D-3	Feb. 8	Upper	2.7597		5.559		1.972		0.0031	
		Inter.	2.7436	0.442	4.906	11.2	2.234		0.0043	
		Lower	2.7418		5.523		1.984	0.0179	0.0074	0.0105
D-4	Feb. 8	Upper	2.3051		4.648		0.923		0.0007	
		Inter.	2.3011	0.442	4.021	13.3	1.067		0.0010	
		Lower	2.3004		4.640		0.925	0.0047	0.0017	0.0030
D-4	Feb. 8	Upper	2.3155		4.671		0.920		0.0007	
		Inter.	2.3119	0.442	4.043	13.2	1.062		0.0010	
		Lower	2.3112		4.660		0.922	0.0043	0.0017	0.0026

TABLE 2, APPENDIX E—Continued.

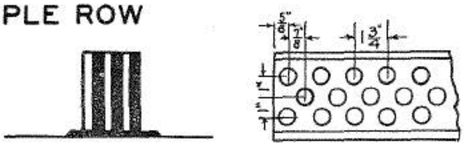
Observed Data of Experiments in Hydraulics Laboratory, University of Michigan, 1932.

PILE MODEL, DOUBLE ROW



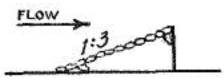
Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
D-5	Feb. 10	Upper	2.2945		4.628		0.933		0.0007	
		Inter.	2.2912	0.442	4.153	10.1	1.040		0.0011	
		Lower	2.2903		4.618		0.935	0.0042	0.0018	0.0024

PILE MODEL, TRIPLE ROW



Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
D-6	Feb. 8	Upper	1.8371		3.708		2.964		0.0082	
		Inter.	1.7883	0.442	3.140	12.0	3.500		0.0126	
		Lower	1.7666		3.568		3.080	0.0705	0.0208	0.0497
D-7	Feb. 10	Upper	2.2347		4.507		2.438		0.0051	
		Inter.	2.2079	0.442	3.986	10.3	2.757		0.0074	
		Lower	2.2029		4.443		2.474	0.0318	0.0125	0.0193
D-8	Feb. 10	Upper	2.7758		5.590		1.964		0.0031	
		Inter.	2.7614	0.442	5.095	8.4	2.155		0.0043	
		Lower	2.7606		5.561		1.974	0.0152	0.0074	0.0078
D-9	Feb. 9	Upper	2.2832		4.604		0.931		0.0007	
		Inter.	2.2801	0.442	4.130	10.1	1.037		0.0011	
		Lower	2.2786		4.595		0.933	0.0046	0.0018	0.0028
D-9	Feb. 9	Upper	2.2829		4.604		0.929		0.0007	
		Inter.	2.2795	0.442	4.128	10.2	1.036		0.0011	
		Lower	2.2788		4.595		0.931	0.0041	0.0018	0.0023

STONE MODELS

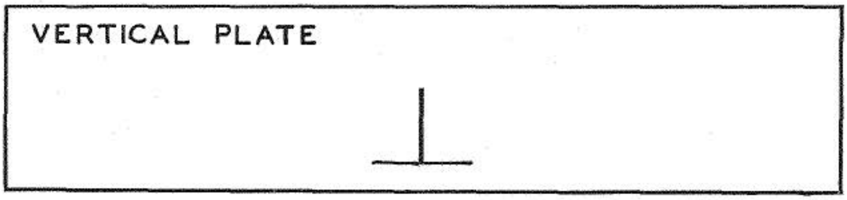


Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
F-3	Feb. 15	Upper	2.2978		4.632		0.935		0.0007	
		Inter.	2.2910	0.4428	3.722	19.3	1.164		0.0011	
		Lower	2.2944		4.625		0.937	0.0034	0.0018	0.0016

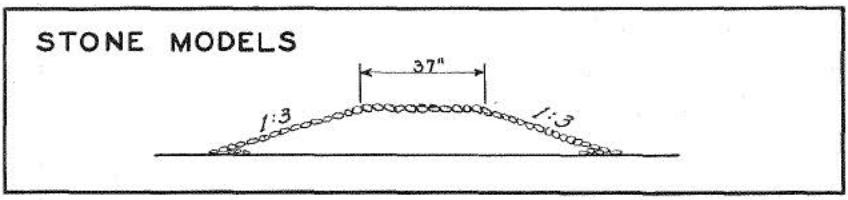
TABLB 2, APPENDIX E—Continued.

Observed Data of Experiments in Hydraulics Laboratory, University of Michigan, 1932.

Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
F-5	Feb. 16	Upper	2.6910		5.420		0.811		0.0005	
		Inter.	2.6800	0.8453	3.686	31.5	1.193		0.0007	
		Lower	2.6851		5.409		0.813	0.0059	0.0012	0.0047



Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
F-1	Feb. 10	Upper	1.9282		3.890		2.817		0.0072	
		Inter.	1.8094	0.4428	2.751	24.5	3.984		0.0122	
		Lower	1.7938		3.620		3.028	0.1344	0.0194	0.1150
F-2	Feb. 10	Upper	2.2887		4.615		0.923		0.0007	
		Inter.	2.2788	0.4428	3.697	19.4	1.152		0.0010	
		Lower	2.2813		4.600		0.926	0.0074	0.0017	0.0057
F-4	Feb. 16	Upper	2.6860		5.410		0.815		0.0005	
		Inter.	2.6721	0.8453	3.669	31.6	1.202		0.0008	
		Lower	2.6714		5.382		0.820	0.0146	0.0013	0.0133



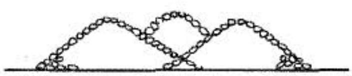
Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
E-1	Feb. 12	Upper	1.8522		3.740		2.947		0.0080	
		Inter.	1.6631	0.4225	2.493	23.3	4.420		0.0122	
		Lower	1.7989		3.629		3.037	0.0533	0.0202	0.0331
E-2	Feb. 12	Upper	2.2310		4.498		2.428		0.0050	
		Inter.	2.1601	0.4225	3.498	19.1	3.122		0.0073	
		Lower	2.2046		4.446		2.456	0.0264	0.0123	0.0141
E-3	Feb. 12	Upper	2.7685		5.575		1.984		0.0031	
		Inter.	2.7400	0.4225	4.660	15.3	2.373		0.0044	
		Lower	2.7580		5.555		1.991	0.0105	0.0075	0.0030
E-4	Feb. 12	Upper	2.2941		4.625		0.920		0.0007	
		Inter.	2.2876	0.4225	3.756	18.4	1.133		0.0010	
		Lower	2.2916		4.622		0.921	0.0025	0.0017	0.0008
E-4	Feb. 12	Upper	2.2955		4.627		0.919		0.0007	
		Inter.	2.2894	0.4225	3.758	18.4	1.131		0.0010	
		Lower	2.2932		4.624		0.919	0.0023	0.0017	0.0006

TABLE 2, APPENDIX E—Continued.

Observed Data of Experiments in Hydraulics Laboratory, University of Michigan, 1932

Reference No.	Date	Gage	Water Surface Above Mean Bottom *Feet*	Height of Weir *Feet*	Areas *Sq. Feet*	Percentage Obstruction	Velocities *Ft. per Sec.*	Falls in Feet Observed	Falls in Feet Normal	Backwater *Feet*
E-5	Feb. 13	Upper	2.6732		5.386		0.822		0.0005	
		Inter.	2.6606	0.8185	3.700	30.7	1.196		0.0008	
		Lower	2.6685		5.375		0.824	0.0047	0.0013	0.0034
E-5	Feb. 13	Upper	2.6815		5.402		0.817		0.0005	
		Inter.	2.6687	0.8185	3.714	30.6	1.189		0.0008	
		Lower	2.6769		5.394		0.819	0.0046	0.0013	0.0033

IRREGULAR STONE PILES



E-6	Feb. 17	Upper	2.3024		4.643		0.933		0.0007	
		Inter.	2.2975	0.443	3.976	14.3	1.090		0.0010	
		Lower	2.2998		4.637		0.934	0.0026	0.0017	0.0009